

USE OF GEOMEMBRANES IN BUREAU OF RECLAMATION CANALS, RESERVOIRS, AND DAM REHABILITATION

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13. ABSTRACT (Maximum 200 words) This report summarizes Bureau of Reclamation experiences with geomembranes for seepage control in canals, reservoirs, and dams. This report also presents design criteria, construction procedures, and O&M considerations for buried geomembrane canal linings. Results indicate that buried geomembranes are generally providing satisfactory service for seepage control, and that they are viable alternatives in area not suitable for concrete or compacted earth linings. Some problems have been encountered with slope stability of the protective soil cover on steeper slopes, and additional studies are needed concerning the stability problem. Laboratory studies and field observations indicate that some stiffening of PVC geomembrane has resulted in a reduction in elongation, and increase in tensile strength, and a decrease in resistance to damage at low temperatures.				
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**Use of Geomembranes in
Bureau of Reclamation Canals,
Reservoirs, and Dam Rehabilitation**

**by
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December 1995

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GLOSSARY

ASTM	=	American Society for Testing and Materials
CPE-R	=	Reinforced chlorinated polyethylene
CSPE-R	=	Reinforced chlorosulfonated polyethylene
EIA	=	Ethylene interpolymer alloy
EIA-R	=	Reinforced ethylene interpolymer alloy
EPDM	=	Ethylene propylene diene monomer
FML	=	Flexible membrane lining
GM	=	Geomembrane
GT	=	Geotextile
HDPE	=	High density polyethylene
HDPE-A	=	High density polyethylene alloy
HDPE-T	=	Textured high density polyethylene
LCCL	=	Lower cost canal lining
LDPE	=	Low density polyethylene
LLDPE	=	Linear low density polyethylene
LLDPE-T	=	Textured linear low density polyethylene
n	=	Manning's coefficient of roughness
NSF	=	National Sanitation Foundation
OCCS	=	Open and Closed Conduit Systems
O&M	=	Operation and maintenance
PE	=	Polyethylene
PP	=	Polypropylene
PP-T	=	Textured polypropylene
PVC	=	Polyvinyl chloride
Q	=	Flow rate
R&B	=	Rehabilitation and betterment
r	=	Hydraulic radius
s	=	Slope
s:s	=	Ratio of side slopes
VLDPE	=	Very low density polyethylene
VLDPE-T	=	Textured very low density polyethylene
WATER	=	Water and Environmental Research

INTRODUCTION

This report summarizes Bureau of Reclamation experiences with geomembranes for seepage control in canals, reservoirs, and dam rehabilitation. The term "geomembrane," adopted by industry both in the United States and worldwide, includes such materials as synthetic linings, plastic linings, flexible membrane linings, etc. In total, Reclamation has installed over 4,000,000 m² (5,000,000 yd²) of geomembrane canal liner since 1968; 1,400,000 m² (1,700,000 yd²) of geomembrane reservoir liner since 1980; and 80,000 m² (100,000 yd²) of geomembrane for dam rehabilitation since 1985.

Reclamation's 35+ years of geomembrane experience are briefly summarized in table 1. Geomembranes have proven especially effective where limited access, short downtime, long haul distances, and potential for freezing and thawing are factors.

This report contains the following items:

1. Conclusions and recommendations
2. Background information
3. Design criteria for buried membrane linings
4. Construction procedures
5. O&M considerations
6. Canal field studies
7. Reservoir applications
8. Dam rehabilitation applications
9. Special applications
10. Laboratory studies
11. Bibliography

Table 1. - Reclamation experience with geomembranes.

Typical Geomembranes	Biaxial Flexibility	Uniaxial Elongation	Conformance to Subgrade	UV Resistance	Thermal Expansion	Shear Friction	Ease of handling ¹	Seaming Methods	Point Puncture Resistance
PVC	Very Good	Good	Very Good	Not Recommended ²	Low to Moderate	Low	Prefabricated Panels easy	Chemical Thermal	Good
PVC-geotextile	Low	Restrained by Geotextile	Good	Generally Not Recommended	Restrained by Geotextile	High	Rolls	Chemical Thermal	Good
CSPE-R/CPE-R	Low	Restrained by Scrim	Good	Good	Restrained by Scrim	Moderate	Prefabricated Panels	Chemical Thermal	Low
EIA	Good	Good	Good	Good	—————	Low	Rolls	Chemical Thermal	Good
EIA-R fabric	Low	Restrained by Fabric	Moderate	Good	Restrained by Fabric	Moderate	Rolls	Chemical Thermal	Low
HDPE	Low	Design @ yield	Low	Good	High	Very Low	Rolls (stiff)	Thermal	Low
HDPE-T	Low	Design @ yield	Low	Good	High	High	Rolls (stiff)	Thermal	Low
VLDPE	Excellent	Excellent	Moderate	Not Good	High but flexible	Low	Rolls	Thermal	Excellent
VLDPE-T	Excellent	Good	Moderate	—————	High but flexible	High	Rolls	Thermal	Excellent
LLDPE	Excellent	Excellent	Moderate	Good	High but flexible	Low	Rolls	Thermal	Excellent
LLDPE-T	Excellent	Good	Moderate	—————	High but flexible	High	Rolls	Thermal	Excellent
PP	Excellent	Excellent	Good	Good	Low	—————	Panels or Rolls	Thermal	Excellent
PP-T	—————	Good	—————	—————	Low	—————	Panels or Rolls	Thermal	Excellent
Polymer Mod. Bituminous	—————	—————	OK	Surface Crazing	—————	—————	Heavy Rolls	Liquid Asphalt Thermal	—————

————— Has not been tested

¹ Packaging - prefabricated panels generally require less field seaming than rolls

² Not recommended for long-term exposure unless specially formulated for UV and of sufficient thickness

CONCLUSIONS AND RECOMMENDATIONS

1. Buried geomembranes are providing satisfactory seepage control in Reclamation canals, dams, and reservoirs. These linings are viable alternatives to concrete and compacted earth linings.
2. Laboratory studies and field observations indicate that some stiffening of PVC geomembranes has occurred with time. Stiffening or aging is caused by the loss of plasticizer, the agent used in geomembrane manufacturing to impart flexibility. A reduction in elongation, a tensile strength increase, and a decrease in resistance to impact damage generally accompany aging. The reduction in resistance to impact was quite evident for samples damaged by shovels during their removal from the canals. To avoid such damage to the geomembrane in future work, coupon samples should be installed and retrieved as a means of monitoring the performance of the primary liner. Impact damage was also observed for linings that had been exposed to animal traffic.
3. The rate of aging (plasticizer loss) of PVC geomembranes depends primarily upon the following factors:
 - PVC geomembrane source.—56-day laboratory volatility tests indicate differences in plasticizer loss rates among PVC linings from different manufacturers.
 - Thickness of PVC geomembrane.—Results of 56-day laboratory volatility tests also indicate that the plasticizer loss rates generally decrease with an increase in geomembrane thickness.
 - Location in canal.—Samples obtained from within the water prism generally exhibited less aging than those obtained above the waterline.
 - Condition of subgrade.—Samples obtained from areas where the geomembrane has been placed over a fairly smooth subgrade exhibited less aging than those installed over a coarser base.
4. Geomembranes frequently require some type of soil cover to protect them from the elements, animal traffic, vandalism, and mechanical damage during cleaning operations. The side slopes should be constructed sufficiently flat to ensure that the soil cover remains stable on the slopes under operating conditions. In earlier plastic lining work, 2 H (horizontal) to 1 V (vertical) side slopes were used, but experience has shown that, in many locations, this ratio is borderline with respect to soil cover stability. Generally, 2.5:1 is stable for smooth GM, and 2:1 is borderline (may or may not sluff depending on the specific soil and GM). For textured GM or GT, 2:1 is usually stable, and 1.5:1 is borderline. With the increased use of geomembranes, particularly with regard to landfills and hazardous waste disposal, new design criteria have been developed concerning slope stability of geomembrane-lined facilities. The current state of practice (Koerner, 1990) suggests that, when at all possible, site-specific friction tests are recommended. Reclamation has investigated the accuracy of these friction tests (Bureau of Reclamation, 1994b) and has found the results quite reliable. The geomembrane industry is currently addressing inadequate friction by developing new products.

5. Related to slope stability is the type of soil cover used. The protective soil cover requirement is one of the major cost items for geomembrane lining construction. To reduce the cost of the protective soil cover, attempts have been made to use excavated material for part of the cover depth, including a 6-in sand/gravel layer for the upper part to provide erosion protection. This approach has generally worked satisfactorily for the rehabilitation work on the Riverton Unit in Wyoming, but mixed results have been obtained on the San Luis Valley Project, Colorado, and the New Rockford Canal. Consequently, because of the increased use of geomembranes in Reclamation's canal work, development of criteria for the earth portion of the protective soil cover system is recommended. For example, clays and silts are generally not suitable because of possible stability problems, whereas criteria for a sand/gravel cover have been fairly well established. Reclamation acquired a new 300- by 300-mm (12- by 12-in) shearbox, and laboratory interfacial friction tests should be initiated on various soil/geomembrane systems to help establish cover soil criteria. If suitable earth materials are not available for a particular site, the use of buried smooth geomembranes would not be advised.
6. Results of recent studies on the South Canal, Belle Fourche Unit, South Dakota, indicate that the polyolefin composite (GT/LDPE/GT) lining has performed satisfactorily for improving soil cover stability on canal side slopes. No slippage of the protective soil cover has been observed on the 1.5 (H) to 1 (V) side slopes in the test section. Additional field studies are recommended at other sites to fully evaluate polyolefin composite effectiveness. In addition to this geomembrane, other materials with frictional surfaces should be included in the field tests.
7. Results of other recent studies on the South Canal, Belle Fourche Unit, South Dakota, indicate that buried 0.75-mm (30-mil) VLDPE has good aging characteristics, and consideration should be given to allow this material as an alternative to PVC in buried membrane lining construction. The U.S. Army Corps of Engineers has included VLDPE as an alternative to PVC in their draft guide specification "Geomembrane For Landfill Cap Systems." Because VLDPE and PP require heat seaming, the minimum thickness should not be less than 0.75 mm (30 mil) in order to reduce the possibility of burning through the lining during the seaming process. After 3 years of field exposure, the buried PP lining also exhibits good aging characteristics.
8. In keeping with the trend of reducing the use of solvent-base construction materials (oil base paints, cutback asphalts, etc.), the field seaming of geomembranes, including PVC, by chemical methods is expected to decrease in the next few years and eventually will be eliminated. To prepare for this eventuality, industry is now beginning to develop heat seaming methods for use in the field. These methods are being developed in addition to those currently being used to heat seam polyolefin-type geomembranes. Some of this new technology is now available. Consequently, it is recommended that consideration be given to increasing the current thickness requirement of PVC in Reclamation canal lining work from 0.5 mm (20 mil) to 0.75 mm (30 mil). As with VLDPE, this thickness is the minimum that can be successfully heat seamed. The additional cost of the heavier gauge PVC should be minimal. The material cost should increase about 40 to 50 cents/m² (4 to 5 cents/ft²), and the thicker material should increase the service life of the geomembrane lining systems.
9. Bottom-only geomembrane linings can be an effective, low-cost method of reducing canal seepage in loessial soils. In studies conducted in cooperation with the Nebraska-Kansas Projects Office, a seepage reduction of 50 to 60 percent was obtained in three canals when

0.25-mm (10-mil) PVC was installed only in the canal invert. This seepage control method can be easily accomplished by local field personnel.

10. The successful completion of the 2.4-km (1.5-mi) long demonstration section on the Coachella Canal, California, has shown the feasibility of the underwater lining of operating canals as a seepage control method. Some additional studies are needed, however, to optimize the concrete mix, determine the influence of side slope steepness, and evaluate other geomembrane lining materials. Refinement of techniques will allow the underwater lining of canals to find wide use, both in the southwestern United States and worldwide. The underwater lining technology is also applicable to placement in the dry. For example, the concrete/geomembrane could be used to avoid overexcavation in expansive clays or shales, gypsiferous and loessial soils, and high-sulfate soils.
11. Recent experiences on the Putah South Canal, Solano Irrigation District, California; the Mirdan Canal, North Loup Division, Nebraska; and the Tucson Aqueduct Reach 3, Tucson Division, Central Arizona Project indicate that geomembranes can be used for the expedient repair of deteriorated concrete linings. A shotcrete/geomembrane lining system has performed satisfactorily since installation in November 1989 on the Putah South Canal. On the Mirdan Canal, geomembranes were used alone as exposed linings for temporary repair, and in combination with a fabric form concrete protective material for permanent repair. The shotcrete/geosynthetic repair technique was successfully installed in December 1994 to repair about 2.4 kilometers (1.5 mi) of the Tucson Aqueduct Reach 3 concrete lining. With over 8000 km (5000 mi) of concrete linings in varying degrees of condition on Reclamation projects, additional studies are recommended to fully evaluate the effectiveness of geomembranes for the repair of these conveyance systems. Their use would be advantageous, especially in applications where conventional construction materials are not available, or cannot be used because of weather conditions, time constraints (for example, minimum downtime to accomplish the repair), limited access, etc.
12. Recent repair efforts on several dams indicate the effective use of CSPE-R for emergency spillways and textured VLDPE for seepage control of aging embankment dams.
13. Results of studies conducted on the geomembrane installed in 1980 in the Mt. Elbert Forebay Reservoir, Fryingpan-Arkansas Project, Colorado, indicate that the material is performing satisfactorily. The studies involved continuous monitoring of the instrumentation on the hillside between the forebay reservoir and powerplant, and periodic retrieval of coupon samples from the field test section for laboratory testing and evaluation. At the time, this installation constituted the world's largest single-cell geomembrane lining application (117 ha[290 acres]) and represented a milestone in the use of geosynthetic materials in the United States, if not in the world.

BACKGROUND INFORMATION

Much of Reclamation's developmental work on geomembranes has been for canal applications and was accomplished under Reclamation's LCCL (lower cost canal lining) program which ran from 1945 to 1967, and its successor, the OCCS (open and closed conduit systems) program conducted from 1967 to 1989. Bureau of Reclamation (1963), Hickey (1969), and Morrison and Starbuck (1984) summarize some of the developmental work. In addition, since the early 1980s, PVC (polyvinyl chloride) has been used widely as a canal lining material in Southern Alberta, Canada (Weimer, 1987).

Canals are unique structures because they are long and narrow, have limited access for work, and have steep side slopes. Historically, PVC has been the most widely used geomembrane for canal applications for the following reasons:

1. Availability in large sheets.—PVC can be factory-fabricated into panels up to 30 m wide and 100 to 200 m long. The liner can be accordion-folded in both directions to facilitate shipping and handling in the narrow confines associated with canal construction. These large panels minimize field seaming.
2. PVC is highly flexible and retains this property over a wide range of temperatures, which permits it to conform to the subgrade better than other geomembrane materials which were available at the time of selection.
3. PVC is easily field-spliced and repaired with a solvent-type cement.
4. PVC also has good puncture, abrasive, and tear-resistant properties, which are important to minimize damage during installation.
5. PVC geomembrane installation does not require much sophisticated equipment or skilled labor.

Reclamation's earliest PVC geomembrane installation was a small experimental section installed in 1957, on the Shoshone Project in Wyoming. The first PVC installation under a construction specifications was in 1968, on the Helena Valley Canal in Montana (Bureau of Reclamation, 1968). The geomembrane was an alternative to the hot, spray-applied asphalt membrane (Geier and Morrison, 1968). Because the energy crisis in the 1970s caused a significant increase in the cost of petroleum products and limited the source of supply, the asphalt membrane was deleted from the specifications.

Geomembranes were originally used in R&B (rehabilitation and betterment) programs to line previously unlined canals, especially in areas unsuitable for compacted earth or concrete linings. Compacted earth linings become too expensive when haul distances are great. Concrete linings require frequent repair when subjected to freeze/thaw conditions. In addition to the Helena Valley Canal, PVC geomembranes were used in rehabilitation work on the East Bench Unit Montana; Riverton Unit, Wyoming (Wilkerson, 1984); Farwell Unit, Nebraska; Yakima Project, Washington; Grand Valley Project, Colorado; and Belle Fourche Unit, South Dakota. Further information on some of these installations will be presented under the section entitled "Canal Field Studies."

Geomembranes are now frequently specified for new construction. For example, a 0.5-mm (20-mil) PVC plastic was recently used on the San Luis Valley Project, Colorado, to line a conveyance channel for delivering salvaged ground water as a supplemental source to the Rio Grande River (Starbuck and Morrison, 1984; Morrison, 1985). During the preliminary design stage, unreinforced concrete and compacted clay were also considered as possible alternative lining materials. However, high ground water and cold winter temperatures precluded the use of concrete linings, and chemical analyses of the available clay source indicated that it was dispersive and would not be suitable for use as a compacted earth lining.

The installation on the San Luis Valley Project, completed between 1983 and 1987, is the largest use to date of a geomembrane in canal construction in the United States. Over 1,025,000 m² (1,200,000 yd²) of PVC were installed. Geomembranes are also being used in new construction on the New Rockford Canal, Garrison Unit, North Dakota, and on the Kent Canal, North Loup Division, Nebraska.

A list of all Reclamation canal installations where geomembranes have been used is summarized in table 2.

Table 2.-Bureau of Reclamation canal installations using plastic membrane lining.

Spec. No.	Canal	Date of Installation	Material (thickness)	Area Lined	
				m ²	yd ²
604C-72	Helena Valley Canal Helena Valley Unit, Montana	10/68-04/69	PVC (10 mil)	24,700	29,560
604C-77	East Bench Canal East Bench Unit, Montana	10/69-04/70	PVC (10 mil)	72,000	86,100
604C-81	Helena Valley Canal Helena Valley Unit, Montana	10/70-04/71	PVC (10 mil)	23,800	28,440
400C-432	Cottonwood Creek Huntington Canal Emery County Project, Utah	10/70	PVC (10 mil)	20,800	24,850
604C-85	East Bench Canal East Bench Unit, Montana	10/71-10/72	PVC (10 mil)	23,300	27,850
604C-86	Helena Valley Canal Helena Valley Unit, Montana	10/71-10/72	PVC (10 mil)	34,000	40,660
617C-97	Pilot Canal Riverton Unit, Wyoming	10/75-04/76	PVC (10 mil)	6,190	7,400
617C-99	Wyoming & Pilot Canals Riverton Unit, Wyoming	10/75-04/76	PVC (10 mil)	36,780	44,000
617C-108	Pilot Canal Riverton Unit, Wyoming	10/76-04/77	PVC (10 mil)	43,640	52,200
63-C0002	Fivemile Lateral Riverton Unit, Wyoming	10/77-04/78	PVC (10 mil)	23,650	28,300

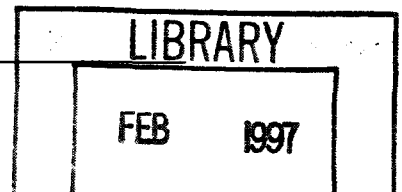


Table 2.-Bureau of Reclamation canal installations using plastic membrane lining (continued).

Spec. No.	Canal	Date of Installation	Material (thickness)	Area Lined	
				m ²	yd ²
63-C0005	Wyoming Laterals Riverton Unit, Wyoming	10/77-04/78	PVC (10 mil)	26,250	31,400
63-C0006	Wyoming Canal Riverton Unit, Wyoming	10/79-04/80	PVC (10 mil)	64,810	77,520
63-C0007	Wyoming & Pilot Canals Riverton Unit, Wyoming	10/77-04/78	PVC (10 mil)	26,840	32,100
63-C0008	Sand Butte Lateral Riverton Unit, Wyoming	10/77-04/78	PVC (10 mil)	19,730	23,600
DC-7248	Amarillo Canal NIIP, New Mexico	06/78-09/78	PVC (10 mil)	13,380	16,000
			PVC (20 mil)	1,590	1,900
			PVC (10 mil)	14,690	17,575
63-C0018	Fivemile Lateral Riverton Unit, Wyoming	10/78-04/79	PVC (10 mil)	13,150	15,730
63-C0015	Pilot Canal Riverton Unit, Wyoming	10/79-04/80	PVC (10 mil)	66,550	79,600
63-C0028	Fivemile Lateral Riverton Unit, Wyoming	10/80-04/81	PVC (10 mil)	13,040	15,600
63-C0032	Pilot Canal Riverton Unit, Wyoming	10/80-04/81	PVC (10 mil)	46,400	55,500
63-C0031	Pilot Canal Riverton Unit, Wyoming	10/81-04/82	PVC (20 mil)	65,380	78,200
63-C0046	Fivemile Lateral Riverton Unit, Wyoming	10/81-04/82	PVC (20 mil)	1,420	1,700
63-C0042	Lost Wells Lateral Riverton Unit, Wyoming	10/82-04/83	PVC (20 mil)	39,710	47,500
63-C0051	Pilot Canal Riverton Unit, Wyoming	10/82-04/83	PVC (20 mil)	41,720	49,900
63-C0054	Wyoming Canal Riverton Unit, Wyoming	10/82-04/83	PVC (20 mil)	30,850	36,900
DC-7553	Conveyance Channel, Reach A, Closed Basin Division, San Luis Project, Colorado	09/83-09/84	PVC (20 mil)	193,116	231,000

Table 2.-Bureau of Reclamation canal installations using plastic membrane lining (continued).

Spec. No.	Canal	Date of Installation	Material (thickness)	Area Lined	
				m ²	yd ²
DC-7571	Conveyance Channel, Reach B, Closed Basin, San Luis Project, Colorado	02/84-04/85	PVC (20 mil)	355,230	401,000
63-C0059	Pavilion Canal Riverton Unit, Wyoming	10/83-04/84	PVC (20 mil)	61,000	73,000
63-C0060	Lost Wells Lateral Riverton Unit, Wyoming	10/83-04/84	PVC (20 mil)	31,000	37,200
63-C0061	Pilot Canal Riverton Unit, Wyoming	10/83-04/84	PVC (20 mil)	33,270	39,800
63-C0062	Wyoming Canal Riverton Unit, Wyoming	10/83-04/84	PVC (20 mil)	60,280	72,100
10-C02280	Kennewick Main Canal, Yakima Project, Kennewick Div., WA	10/83-04/84	PVC (20 mil)	123,700	148,000
DC-7631	Conveyance Channel, Stage 3, Closed Basin Div., San Luis Valley Project, Colorado	03/85-04/86	PVC (20 mil)	313,920	375,500
62-C0061	West Oakes Test Area, Distribution Systems, PSMBP, North Dakota	05/86-09/86	PVC (20 mil)	200,640	240,000
DC-7647	New Rockford Canal, Reach 1A Garrison Diversion Unit, ND	09/86-09/87	PVC (20 mil)	334,400	400,000
DC-7678	Franklin Eddy Canal, Stage 4, Closed Basin Division, San Luis Valley Project, Colorado		PVC (20 mil)	163,100	195,100
DC-7681	West End-Government Highline Canal, Stage 2, Colorado River Basin Salinity Control Project, CO	02/87-05/87	PVC (20 mil)	180,000	215,000
60-C0164	Mirdan Canal, Sec. 1, North Loup Division, Nebraska	09/87-02/88	HDPE (40 mil)	9,200	11,000
DC-7743	Coachella Canal, Inplace Lining Prototype, All-American Canal Relocation, California	02/88-04/91	PVC (30 mil)	82,400	98,560
60-C0183	Mirdan Canal, Sec. 1, North Loup Division, Nebraska	09/88-04/89	PVC (30 mil)	2,717	3,250
DC-7747	New Rockford Canal, Reach 2, Garrison Diversion Unit, ND	08/90-10/91	PVC (20 mil)	654,590	783,000

Table 2.-Bureau of Reclamation canal installations using plastic membrane lining (continued).

Spec. No.	Canal	Date of Installation	Material (thickness)	Area Lined	
				m ²	yd ²
DC-7784	Towaoc Canal, Reach 1, Dolores Project, Colorado	08/90-10/90	PVC (20 mil)	57,600	68,900
69-C0011	Indian Creek Lateral, Stage 2, Belle Fourche Unit, South Dakota	09/90-02/91	PVC (20 mil)	45,830	54,825
DC-7867	Kent Canal & Diversion Structure Grand Island, Nebraska	04/92-09/93	PVC (20 mil)	121,220	145,000
DC-7847	Fullerton Canal, Nebraska	07/91-10/93	PVC (20 mil)	4,930	5,900
DC-7877	East End Govt. Highline Canal Grand Valley Unit, Colorado	07/92-06/95	PVC (20 mil)	302,600	362,000
60-C0251	Courtland Feeder Canal, Phase 1	09/92-11/92	VLDPE (60 mil)	23,900	28,600
			sides exposed (40 mil) bottom gravel covered	14,000	16,800
60-C0284	Courtland Feeder Canal, Phase 2, Station 488+30 to Station 532+83 Station 715+00 to Station 736+36	10/93-05/94 09/94-10/94	VLDPE (60 mil)	39,300	47,000
			sides exposed bottom gravel covered		
60-C0380	Courtland Feeder Canal, Phase 3 Station 451+75 to Station 488+04 Station 537+56 to Station 570+05	09/94-10/94	HDPE (60 mil)	30,000	35,900
			Sides exposed (40 mil) bottom gravel covered	11,000	13,250
60-C0039	South Canal Lining Reach 3, Belle Fourche Unit, South Dakota	10/94-05/95	PVC (20 mil)	19,015	22,745

DESIGN CRITERIA FOR BURIED MEMBRANE LININGS

General

A buried geomembrane system consists of a plastic film covered with a protective layer of earth. Irrigation canals and laterals to be lined should be designed to meet the general requirements of existing standards (Bureau of Reclamation, 1967). The side-slope ratio should be stable for the native soil to ensure that the lining system will not be damaged.

Canals with buried geomembranes must be proportioned to ensure stability of the soil cover. Factors affecting soil cover stability are varied and include: canal velocity and tractive force values; steepness of the canal side slopes; thickness, gradation, and type of soil cover material; amount of soil cover consolidation; type of geomembrane; composition of the subgrade; frost action in the subgrade; wind generated waves; and seepage forces within the soil cover resulting from fluctuating water levels.

Cross Section

Figure 1 shows typical details for a buried geomembrane system. Figure 2 shows the bank height and freeboard requirements for buried membrane linings.

Side slope requirements will vary with different types of membrane and soil cover, but should not be steeper than 2.5 (H) to 1 (V) for smooth geomembrane unless stability studies indicate steeper slopes can be accommodated. Textured geomembrane should be installed no steeper than 2:1 unless stability studies indicate steeper slopes can be accommodated.

The canal cross section should be sized for sufficient capacity to carry the required flow under maximum retardance conditions. The canal should have enough capacity to function as designed without danger of overtopping. The Manning formula is recommended for use in determining the hydraulic properties of the canal. The Manning formula is:

$$Q = \left(\frac{1}{n}\right) A r^{2/3} s^{1/2} \quad (1)$$

where:

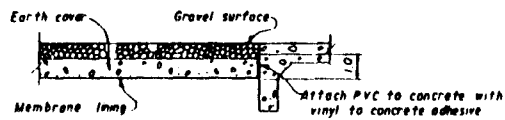
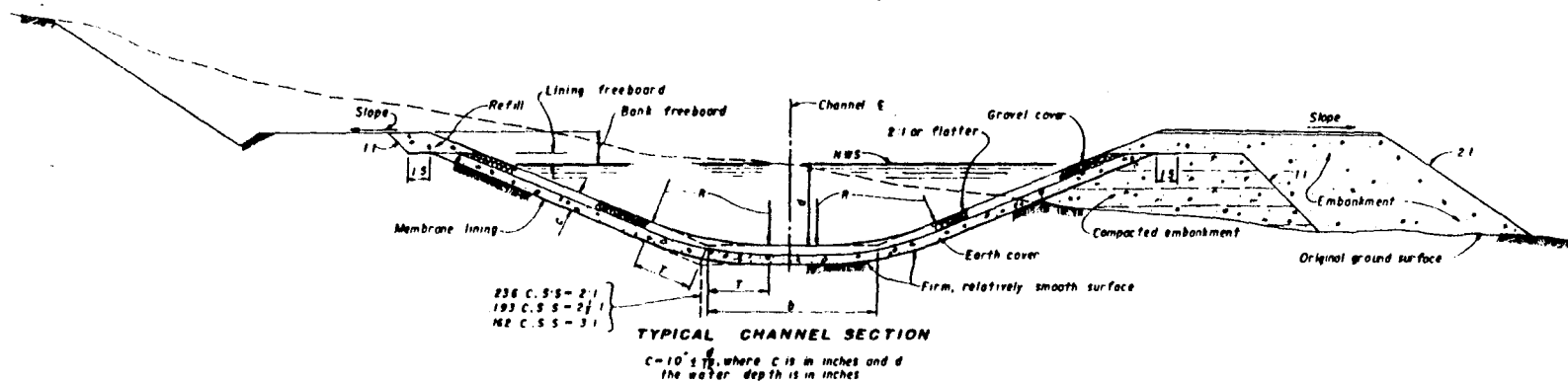
- Q = flow rate in m^3/s
- n = Manning's coefficient of roughness
- A = cross sectional area of flow in m^2
- r = hydraulic radius in m (A/WP , WP = wetted perimeter)
- s = slope of energy gradient (dimensionless)

or

$$Q = (1.486/n) A r^{2/3} s^{1/2} \quad (2)$$

where:

Q is in ft^3/s , A in ft^2 , and r in ft .



b	T	S = 2:1, R = 0.0000 T, AWP = 0.0000 R, A = 0.0000 R^2			S = 3:1, R = 0.0000 T, AWP = 0.0000 R, A = 0.0000 R^2			S = 4:1, R = 0.0000 T, AWP = 0.0000 R, A = 0.0000 R^2		
		R	AWP	A	R	AWP	A	R	AWP	A
2	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
3	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
4	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
5	1.5	6.35	.11	.34	7.79	.07	.28	9.24	.05	.24
6	2.0	8.47	.14	.61	10.39	.10	.50	12.32	.07	.42
8	2.8	11.06	.20	1.20	14.54	.14	.99	17.25	.10	.83
10	3.5	14.03	.25	1.87	18.17	.17	1.54	21.97	.12	1.30
12	4.5	18.22	.31	2.82	22.33	.21	2.32	26.90	.15	1.97
14	5.0	21.18	.36	3.81	25.94	.24	3.14	30.81	.17	2.66
16	5.5	23.30	.40	4.61	28.36	.27	3.80	33.89	.19	3.22
18	6.0	25.42	.43	5.49	31.16	.29	4.52	36.97	.21	3.83
20	6.5	27.33	.47	6.44	33.73	.31	5.31	40.05	.22	4.49
22	7.0	29.65	.50	7.47	36.39	.34	6.16	43.14	.24	5.21
24	7.5	31.77	.54	8.58	38.94	.36	7.07	46.22	.26	5.98
26	7.9	33.47	.57	9.52	41.02	.38	7.84	48.69	.27	6.64
28	8.3	35.16	.60	10.51	43.10	.40	8.66	51.15	.29	7.33
30	8.7	36.85	.63	11.54	45.18	.42	9.51	53.61	.30	8.05
35	9.5	40.24	.68	13.76	49.33	.46	11.34	58.34	.33	9.60
40	10.5	44.48	.76	16.42	54.52	.51	13.83	64.70	.36	11.72
45	11.2	47.44	.81	18.13	58.18	.54	15.76	69.02	.39	13.34
50	12.0	50.83	.86	21.96	62.31	.58	18.09	73.93	.41	15.38

DETAILS OF BURIED MEMBRANE LININGS

NOTES

The gradation, type and thickness of the cover material is dependent on tractive forces and velocities in the section, and the type of material available in the area. A_{WP} is the difference between $2T$ and the arc length. To obtain the wetted perimeter for a section, subtract $2AWP$ from the wetted perimeter for a trapezoidal section of width b . A is the area of the fillet. To obtain the area for a section, subtract $2A$ from the area of a trapezoidal section of width b .

Figure 1. - Typical buried membrane lining section.

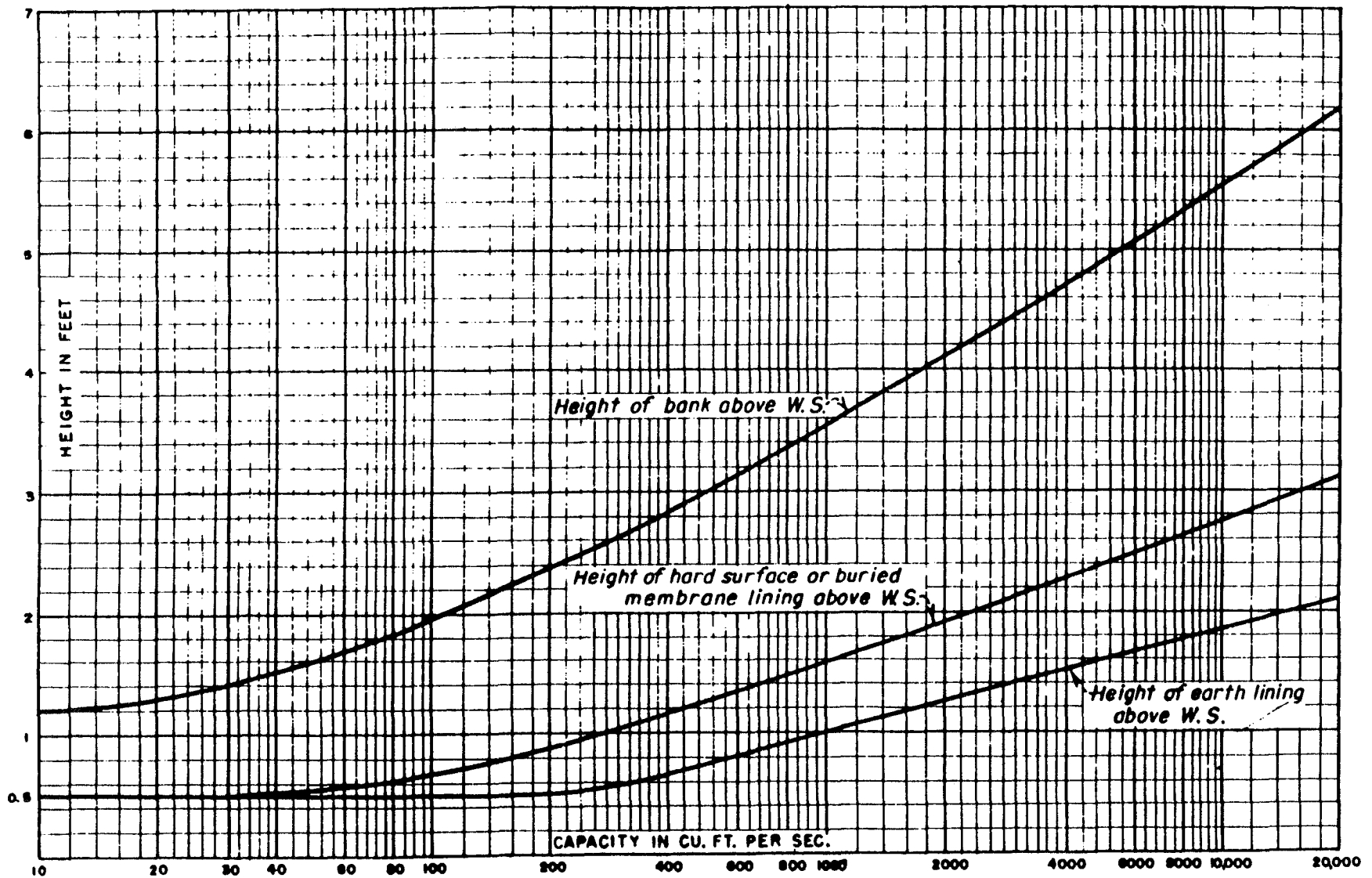


Figure 2. - Bank heights for canals; freeboard for hard surface, buried membrane, and earth linings.

A minimum roughness coefficient n of 0.025 is usually used for earth-lined canals with capacities less than 2.8 m³/s (100 ft³/s); 0.02 to 0.0225 is generally used for larger capacities. The n value for a uniform canal section covered with sand and gravel should be determined from the Strickler equation:

$$n = 0.0342 (d_{50})^{1/6} \quad (3)$$

where d_{50} is the size in feet for which 50 percent of the cover material by weight is finer.

Tractive force limits should be considered to determine canal shape and slope. The limits are based on the gradation of the cover material to be used. Without special studies, the canal velocity should be limited to 0.3 to 1.0 m/s (1 to 3 ft/s), depending on the type of soil cover.

In rehabilitation work, sufficient overexcavation of the earthen structure must take place to provide adequate capacity after covering the membrane.

Cover Material

A soil cover is typically provided on top of a geomembrane to protect it from damage. Sunlight will degrade PVC, and plant growth, maintenance equipment, animal traffic, and vandals may puncture it. A sand and gravel cover is recommended to resist the erosive forces of the flowing water. A 300-mm (12-in) minimum layer of sand and gravel is generally considered adequate protection; however, to minimize sand and gravel requirements, a 150-mm (6-in) layer of sand and gravel may be used, provided an initial layer of protective earth is placed on the PVC. The minimum combined thickness of the two layers should be calculated from the following formula:

$$C = 10 + \frac{d}{12}$$

where:

C = combined thickness of earth and gravel in inches; minimum thickness is 12 in
 d = the water depth in inches

These thicknesses are not adequate where heavy animal traffic (such as at a cattle crossing) is expected. A fenced off, concrete cattle crossing is required in this case.

The gradation of the sand and gravel cover should conform to the limits shown on figure 3. These limits were developed in a study conducted by C.W Jones (1981). Coarser material is generally required in the beach belt area of large canals, where wave action could become severe. Providing material for the sand and gravel cover constitutes a major cost item. If possible, to lower construction costs, the sand and gravel should be obtained from approved borrow areas. Blending material to meet the gradation requirements substantially increases the construction cost. Criteria on the composition of the protective earth layer have not been developed, but clays and silts generally should be avoided. The inclusion of rocks, boulders, vegetable matter, brush, large roots, and other objectionable foreign matter are not permitted.

Generally, neither the protective earth layer nor the sand and gravel cover are consolidated. However, if the sand and gravel cover has marginal gradation characteristics, consolidation of the sand and gravel is recommended.

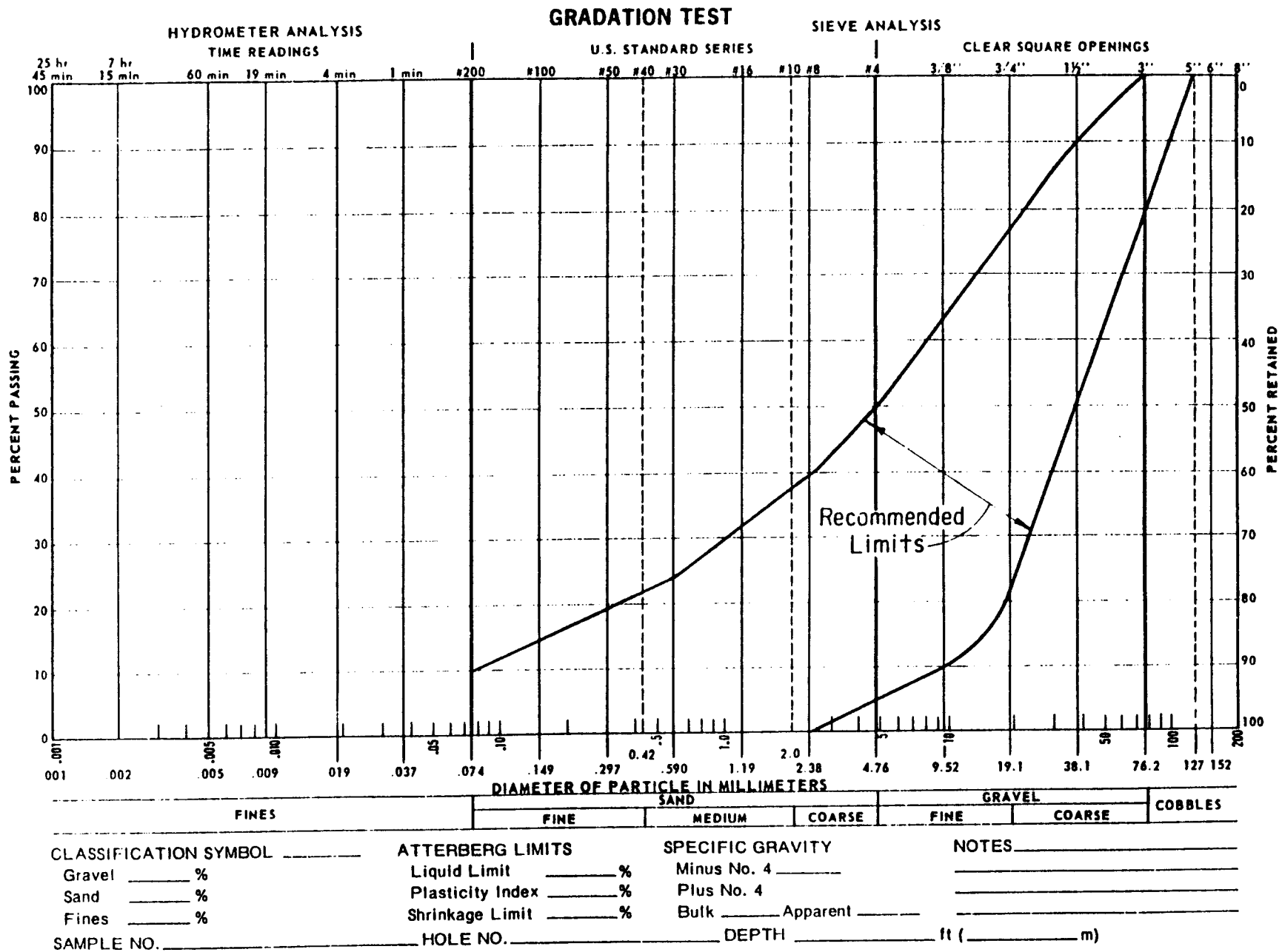


Figure 3. - Sand and gravel cover gradation.

Geomembranes

The currently recommended geomembrane for standard buried canal application is 0.50-m (20-mil) thick PVC. The PVC should conform to the physical property requirements listed in table 1 of NSF (National Sanitation Foundation) Standard 54, Flexible Membrane Liners (NSF, 1993). Several new geomembranes are currently being evaluated for possible use in canal construction. These materials are discussed in the section on canal field studies.

CONSTRUCTION PROCEDURES

General

The installation of geomembranes in R&B work and new construction involves: (1) excavation, (2) subgrade preparation, (3) geomembrane installation, and (4) protective soil cover placement. The following paragraphs describe these construction procedures. R&B work is generally restricted to the nonirrigation season and often involves wintertime construction. On jobs such as the San Luis Valley Project, Colorado (Bureau of Reclamation, 1984; 1985), contractors developed equipment for mechanized geomembrane placement. Cost data for several recent PVC installations are summarized in tables 3 and 4.

Excavation

The side slopes should be constructed sufficiently flat to ensure that the protective soil cover over the geomembrane remains stable on the slopes under operating conditions. Overexcavation of the canal is required for placement of the protective earth cover. Several different excavation methods used in both R&B and new construction are shown on figures 4 and 5.

Subgrade Preparation

After the rough excavation is completed, the subgrade is prepared to a firm, relatively smooth surface. Sharp rocks, roots, and other objects that might puncture the membrane are either removed or padded by covering with 75 to 100 mm (3 to 4 in) of sand or with a non-woven, needle-punched, geotextile cushion.

Dragging the subgrade with a heavy machine-type chain as shown on figure 6, or an arrangement of large timbers and steel rails as shown on figure 7, are rapid and effective methods for preparing the canal subgrade.

Earlier plastic lining construction included a specification requirement for rolling to obtain a smooth subgrade. This particular requirement was a carry over from work with the hot, spray-applied asphalt membrane material (Geier and Morrison, 1968). However, subsequent experience with geomembranes shows that this procedure contributes to slippage of membrane lining and therefore is not usually recommended.

Geomembrane Installation

The PVC lining is supplied to the job site in large, shop-fabricated sheets wide enough to cover the canal prism and to any length practical for handling. To minimize the amount of field seaming, contractors prefer to use lengths up to 100 m (330 ft) for 20-mil PVC. The geomembrane is packaged accordion-folded in both directions and is simply unfolded and pulled into place, as shown on figures 8 through 16.

Installation of plastic lining in a canal is usually started at the downstream end. When tied into concrete structures, the ends of the plastic lining are attached to the concrete as shown on figure 17. Where not tied into structures, the ends of the plastic lining should be buried in 300-mm (12-in) deep transverse cutoff trenches. For most canal work, sheets of PVC lining can be joined simply by lapping the upstream sheet 0.9 m (3 ft) over the downstream sheet.

Table 3.-Cost of PVC lining for New Rockford Canal, Reach 2, Garrison Diversion Unit, North Dakota, PSMBP Specifications No. DC-7747, June 1988.

Hydraulic Properties

Q =	45.3 m ³ /s (1600 ft ³ /s)
V =	0.72 m/s (2.37 ft/s)
bottom width =	1.34 m (44 ft)
water depth =	3.2 m (10.4 ft)
cover depth =	
A. Side slopes, sand/gravel	305 mm (12 in)
B. Bottom, earth	533 (21)
$s:s$	2:1
s	0.00007

Work Description	Quantity & Unit	Engineering estimate/ unit	Bid/ Unit	Cost (\$)
Excavation	231,000 yd ³	1.00	1.11	256,410
Preparing subgrade for membrane lining	780,000 yd ²	0.80	0.20	156,000
Furnishing and placing PVC (20 mils thick)	783,000 yd ²	1.00	1.47	1,151,010
Placing earth cover	354,000 yd ³	1.00	1.49	527,460
Furnishing and placing sand and gravel cover	108,000 yd ³	3.50	8.23	888,840
Total cost				2,979,720
Unit Cost				3.82/yd ²

Table 4. - Cost of PVC lining for Indian Creek Lateral, Stage 2, Belle Fourche Unit, South Dakota, PSMBP Specifications No. 69-C0011, July 1990.

Hydraulic Properties

Q =	3.3 m ³ /s (115 ft ³ /s)
V =	0.60 m/s (1.98 ft/s)
bottom width =	4.3 m (14 ft)
water depth =	0.9 m (2.93 ft)
cover depth =	356 mm (14 in)
$s:s$	2:1
s	0.00040

Work Description	Quantity & Unit	Engineering estimate/ unit	Bid/ Unit	Cost (\$)
Excavation	22,210 yd ³	2.25	1.70	37,570
Preparing subgrade for membrane lining	54,825 yd ²	0.75	0.08	4,386
Furnishing and placing PVC (20 mils thick)	54,825 yd ²	1.75	1.68	92,106
Placing earth cover	9,120 yd ³	2.00	3.00	27,360
Furnishing and placing sand and gravel cover	9,120 yd ³	1.00	6.50	59,280
Refill	4,590 yd ³	1.00	2.40	11,016
Total cost				231,718
Unit Cost				4.23/yd ²



Figure 4. - Backhoe excavation on Pilot Canal, Riverton Unit, Wyoming. In R&B work, overexcavation of the existing canal a minimum of 300 mm (12 in) is required to allow for sufficient space for placement of the protective soil cover.



Figure 5. - Dragline excavation on Wyoming Canal, Riverton Unit, Wyoming.

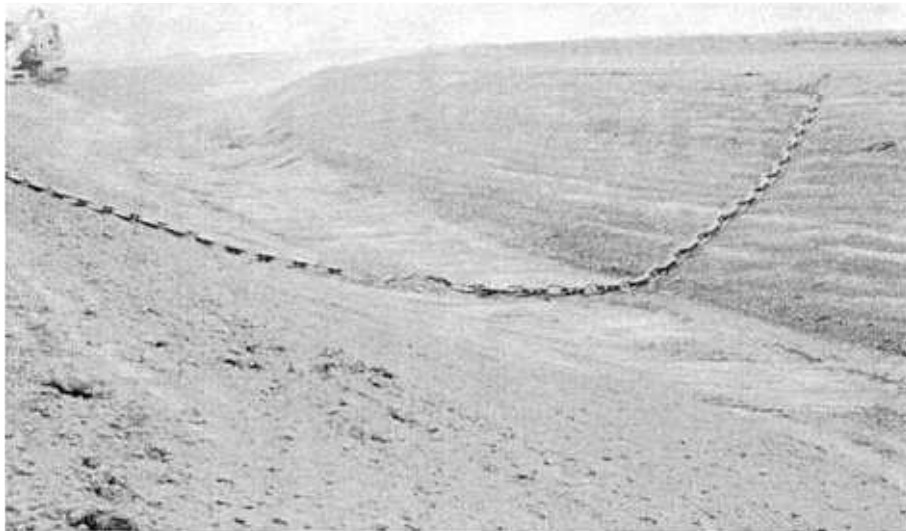


Figure 6. - Dragging canal subgrade with marine-type chain in preparation for PVC geomembrane on Franklin Eddy Canal, San Luis Valley Project, Colorado.

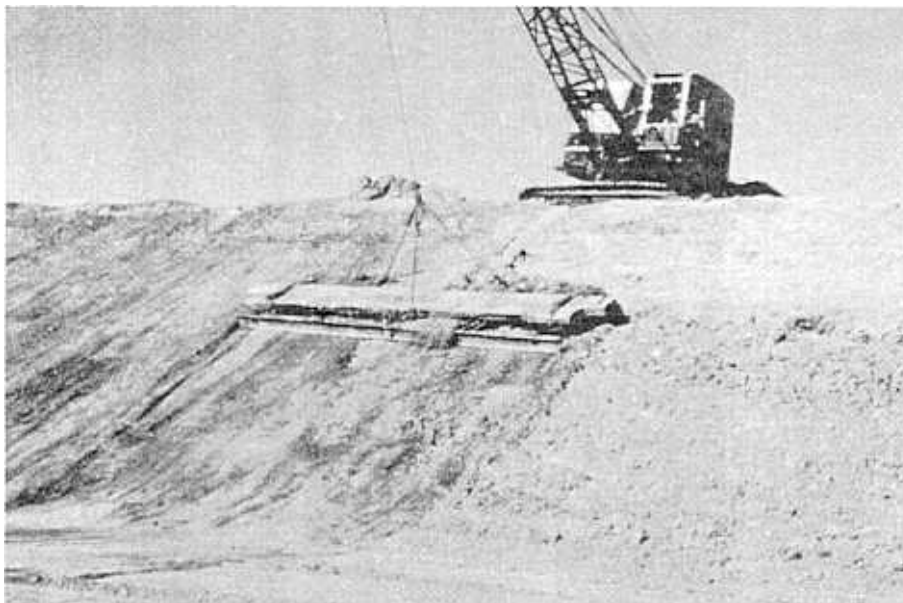


Figure 7. - Arrangement of large timbers and steel rails used by contractor for dragging subgrade in Wyoming Canal, Riverton Unit, Wyoming.



Figure 8. - View of PVC geomembrane as delivered to job site. Geomembrane is packaged accordion-folded in both directions, and is then simply unfolded and pulled into place.



Figure 9. - Unfolding PVC geomembrane.



Figure 10. - Pulling PVC geomembrane into place on side slopes. White streamers are plastic tape placed over factory seam to prevent blocking and sticking of the PVC during shipment.

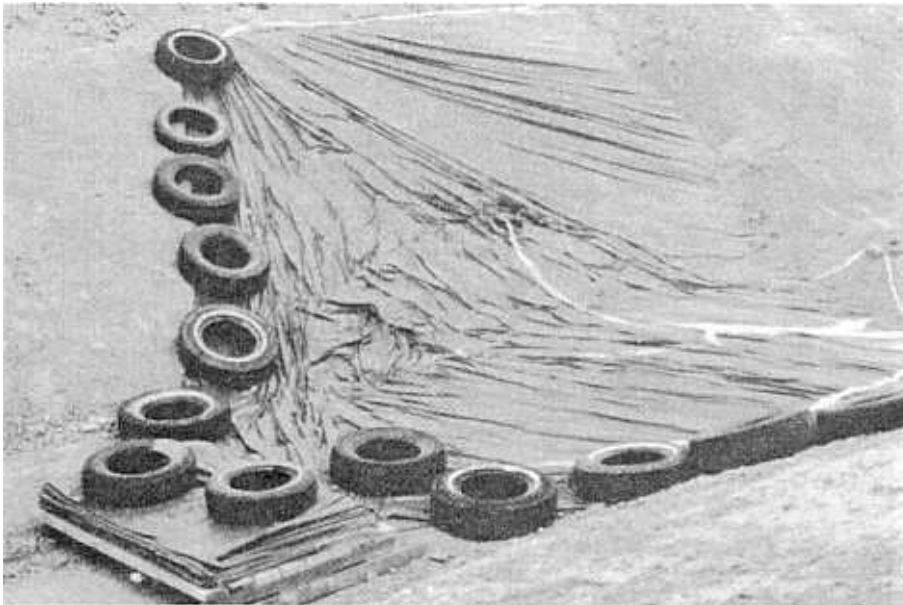


Figure 11. - View of contractor's method of installing PVC geomembrane on Amarillo Canal, Navajo Indian Irrigation Project, New Mexico. Lining was delivered to job site accordion-folded and on pallets. The rubber tires are used to temporarily anchor the lining until earth cover is placed.

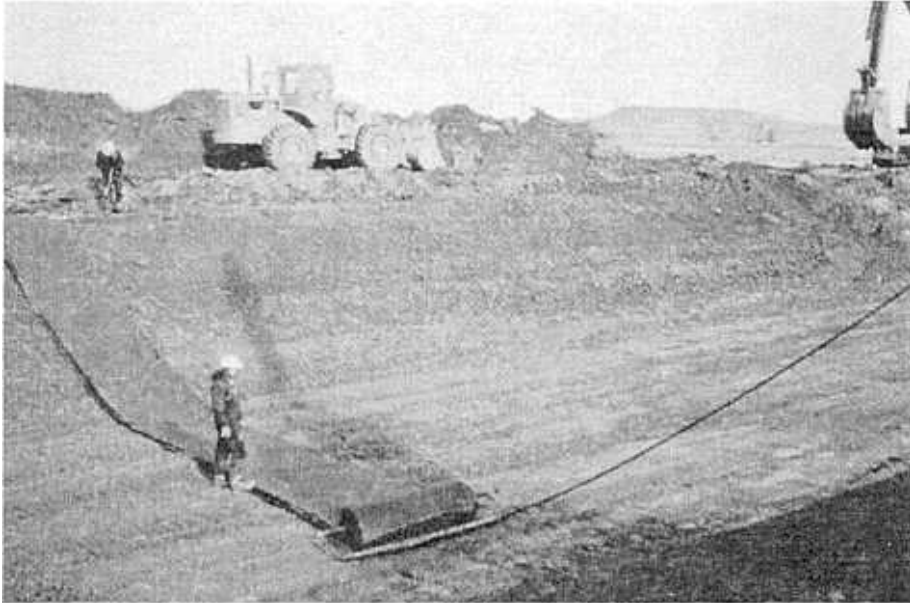


Figure 12. - Installation of PVC in transverse direction.



Figure 13. - View of labor crew unfolding PVC in transverse direction.

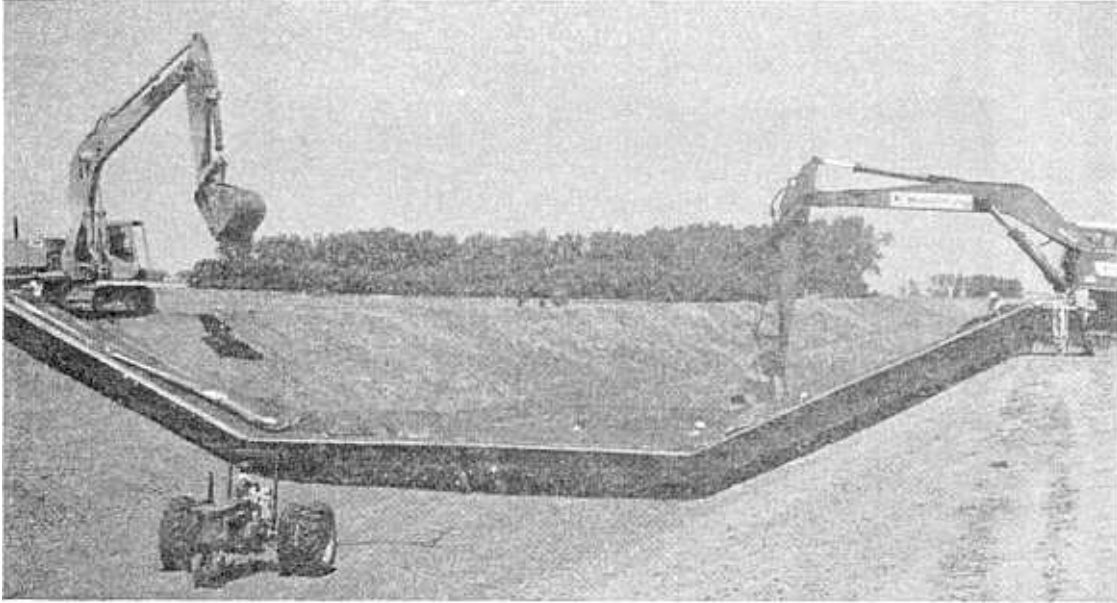


Figure 14. - View of PVC geomembrane ready to be placed from spreading jumbo in New Rockford Canal, Garrison Unit, North Dakota.

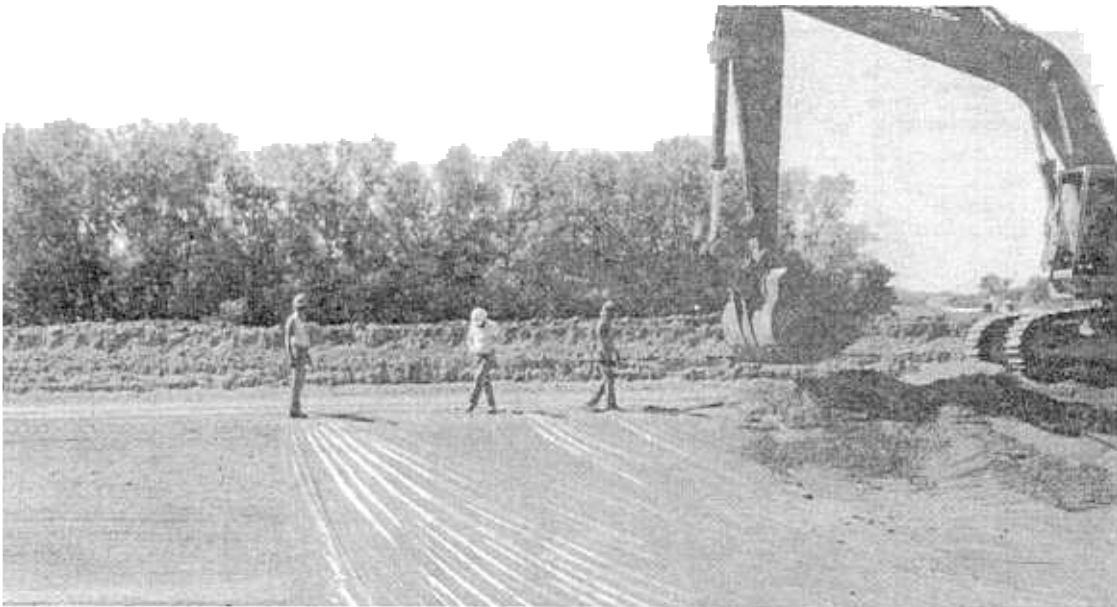


Figure 15. - View of PVC geomembrane clinging to canal subgrade like plastic fold wrap because of high temperatures, about 32 °C (90 °F), during installation in New Rockford Canal.



Figure 16. - View of PVC geomembrane installation around a concrete structure. The PVC will be cut and joined to the structure as shown on figure 17.

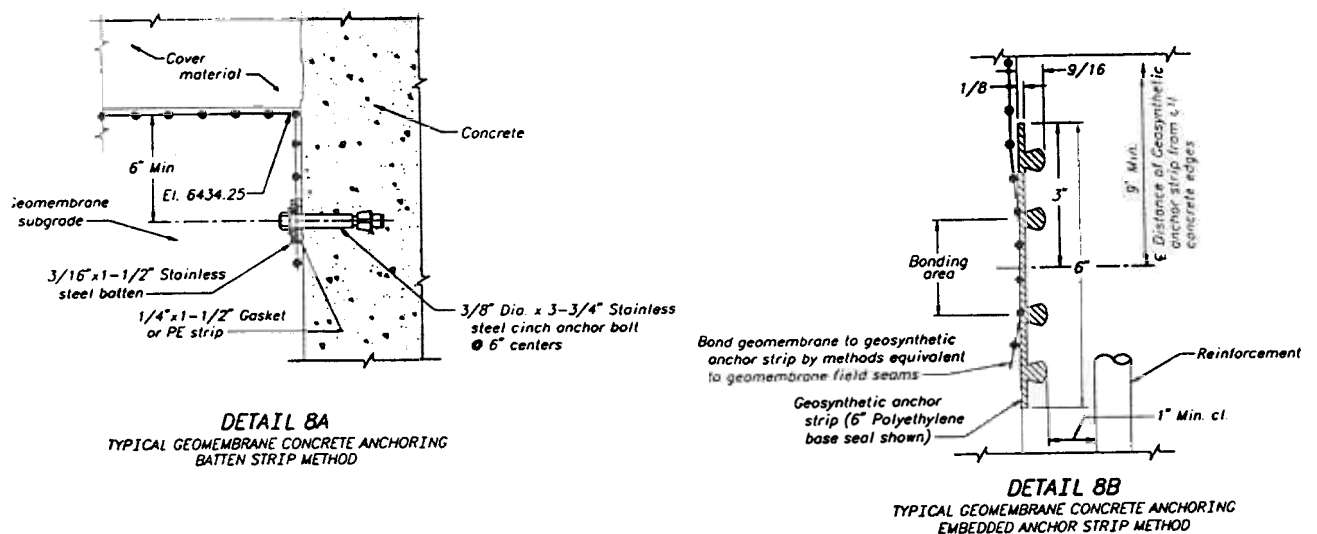


Figure 17. - Methods of anchoring PVC to concrete.

Geomembrane Installation (continued)

The PVC tends to stick to itself and, with the weight of the earth cover, a sufficiently bonded joint is obtained where 100 percent seepage control is not required. Where a more positive seal is required, the PVC should be overlapped a minimum of 300 mm (1 ft), and a solvent cement (recommended by the manufacturer) should be applied to a minimum width of 50 mm (2 in). Current guidelines for field seaming geomembranes are presented in EPA documents (U.S. Environmental Protection Agency, 1991).

When installing PVC around curves, as shown on figure 18, the excess material along the inside of the curve is folded into several small pleats and folded downstream.

The upper edges of the geomembrane should be anchored at the top of the slope as shown on figure 1. To prevent wind damage until the protective soil cover is placed, the geomembrane should be held in place by sandbags (fig. 19), small soil mounds, (fig. 20), discarded rubber tires (fig. 21) or by other satisfactory means. If at all possible, windy weather should be avoided when installing geomembranes (fig. 22); however, if special precautions are taken, plastic lining can be successfully installed during fairly high winds. These precautions are:

1. Place the lining, as nearly as possible, moving in the direction of the wind.
2. Use sufficient personnel to hold the lining tightly to the ground as it is unrolled or unfolded from the container.
3. The geomembrane should be weighted down immediately as it is placed on the subgrade and anchor berms.

It is important that the geomembrane lining is placed in the canal in a slack condition, as shown on figure 23, so that when contraction occurs because of decreasing geomembrane temperatures, the weight of the soil cover will not cause severe stressing. As a rule of thumb, about 5 percent excess slack is generally used.

As previously mentioned on the San Luis Valley Project, Colorado, several contractors developed equipment for the mechanized placement of the geomembrane lining systems. The contractor under Specifications DC-7571 (Bureau of Reclamation, 1983) developed the special trimmer/lining machine shown on figure 24 to place the PVC lining and earth cover in one operation. Rough excavation was accomplished using a backhoe with a twin sloper welded to the bucket. This equipment is shown on figure 25. The local soil was a fine-grained material which was conducive to this type of excavation. The lining machine was equipped with rotary blades which trimmed the canal prism. The excavated material was then moved by conveyor belt as shown on figure 26 to another machine located about 7 m (21 ft) behind the liner machine, which placed the earth cover across the entire perimeter of the canal. This machine, shown on figures 26 and 27, was later backed up and used to place the sand/gravel cover. The PVC lining was stored on a platform attached to the rear of the trimmer/lining machine, from where it was continually placed into the canal. The construction sequence is shown on figures 28 through 30.

Under Specifications No. D-7631 (Bureau of Reclamation, 1984), another contractor developed similar equipment for the mechanized placement of the PVC. This equipment is shown on figures 31 through 34.



Figure 18. - Installation of PVC geomembrane around curves.

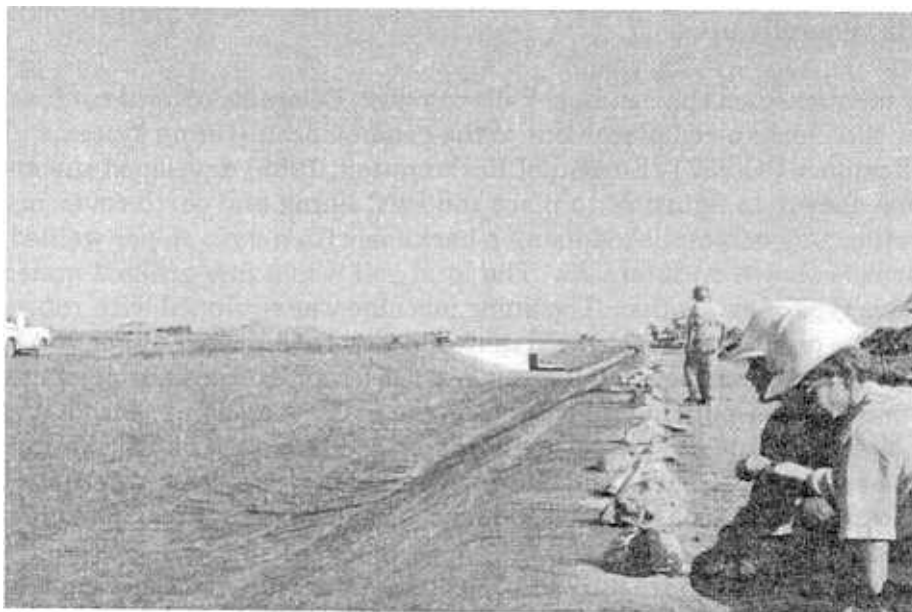


Figure 19. - View of sandbags used to temporarily anchor PVC geomembrane on canal berm.

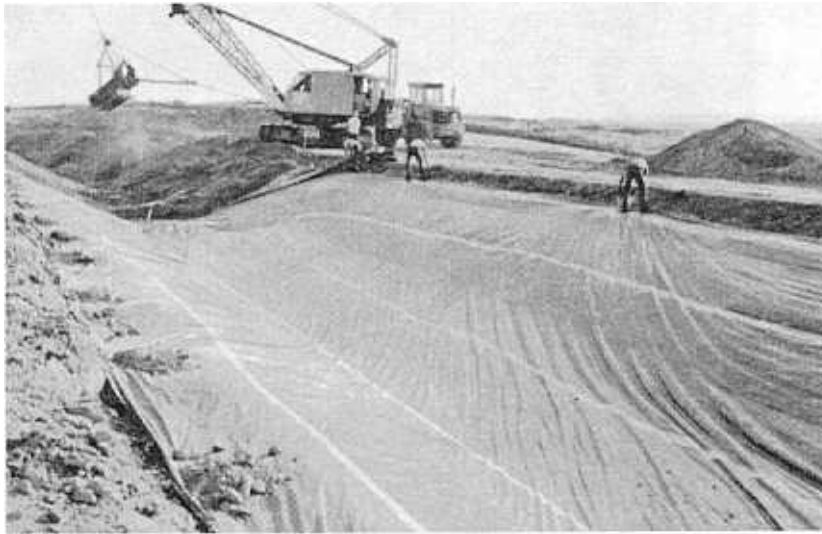


Figure 20. - View of soil mounds to temporarily anchor PVC geomembrane.



Figure 21. - Use of rubber tires to temporarily anchor geomembrane until protective soil cover is placed.



Figure 22. - View of wind picking up light-weight PVC geomembrane.



Figure 23. - View of PVC geomembrane placed in slack condition so that weight of the protective soil cover will not cause severe stress when placed.

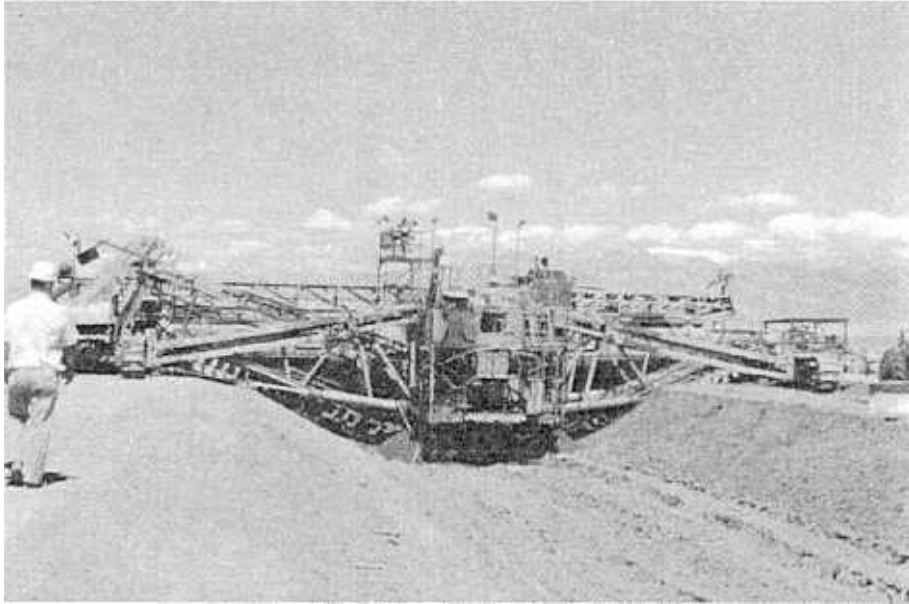


Figure 24. - View of equipment for the mechanized placement of the PVC/protective soil cover. This lining machine is equipped with rotary blades which trim the canal prism. The excavated material is carried by conveyor belt, shown at left, to another machine shown on figure 26, which places it across the entire canal perimeter.



Figure 25. - Rough excavation was accomplished using a backhoe, to which twin slopers have been welded to the bucket as shown. The local soil is a fine-grained material which is conducive to this type of excavation.

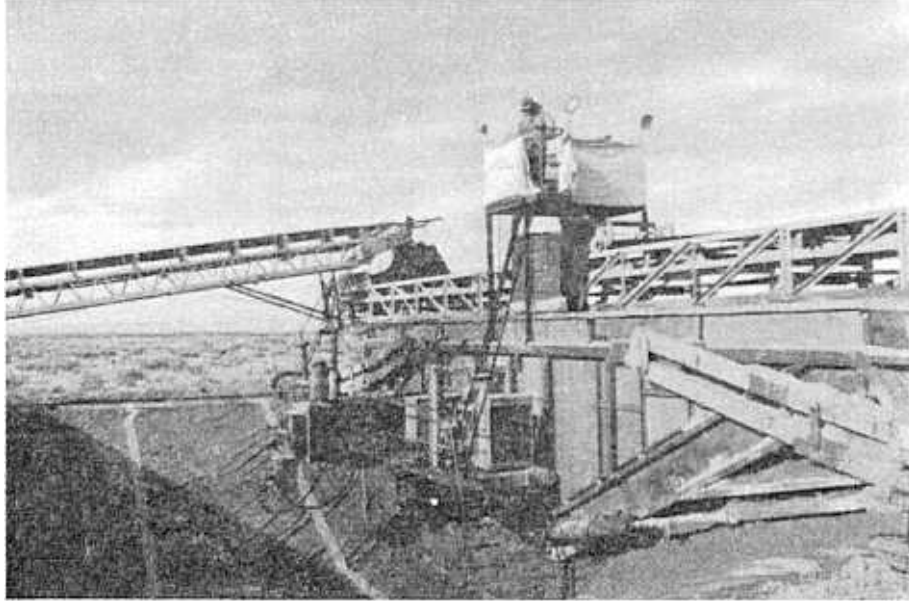


Figure 26. - Machine used to place soil cover. A small cart on tracks moves back and forth across the canal, dumping the excavated materials as it travels. The cart is fed by the conveyor belt.

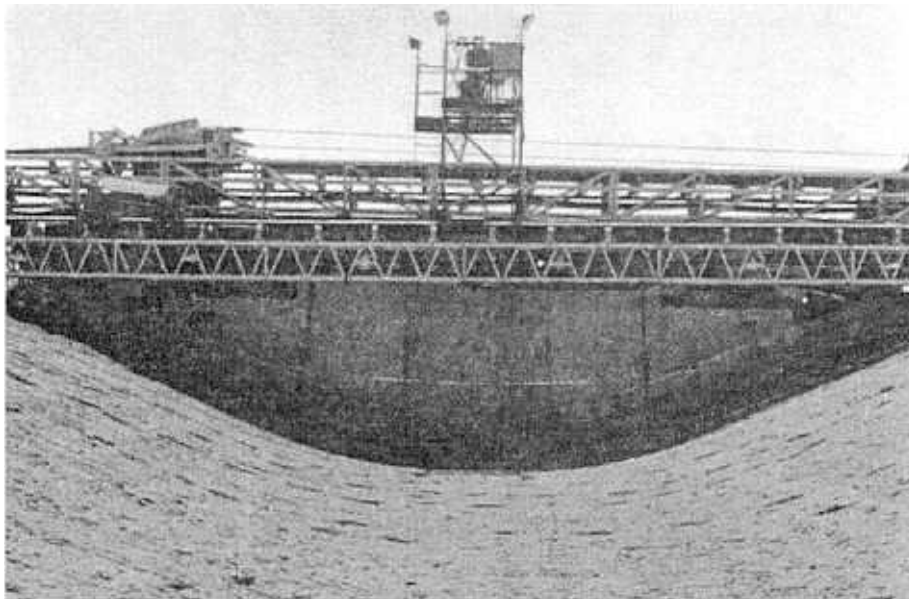


Figure 27. - View of back side of machine shown on figure 26.

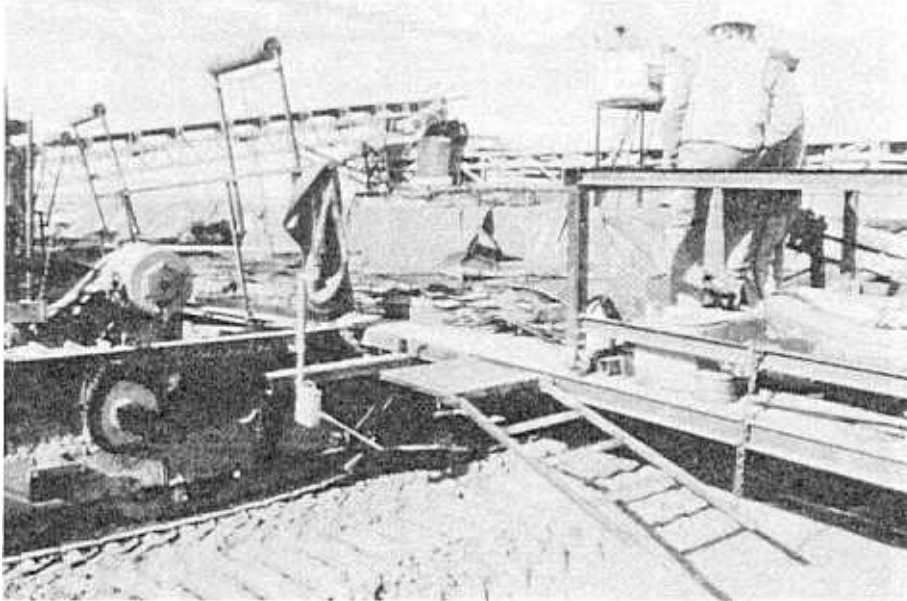


Figure 28. - The PVC geomembrane is stored on a platform attached to the rear of the trimmer/lining machine from where it is continually placed into the canal.

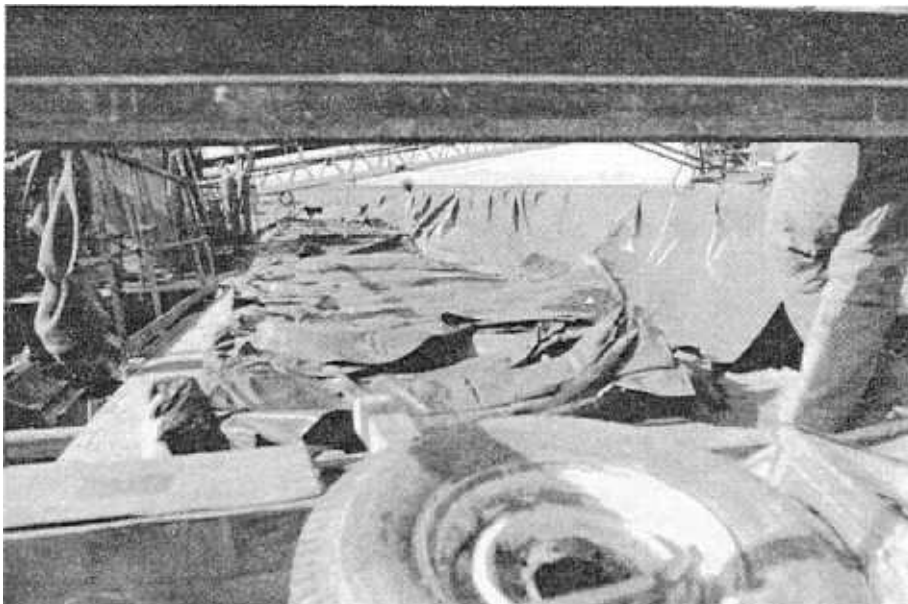


Figure 29. - The PVC geomembrane is shipped from the fabricator accordion folded in the transverse direction so that it can be placed across the entire canal width. The sheets were about 20 m (60 ft) wide by 100 m (300 ft) long.

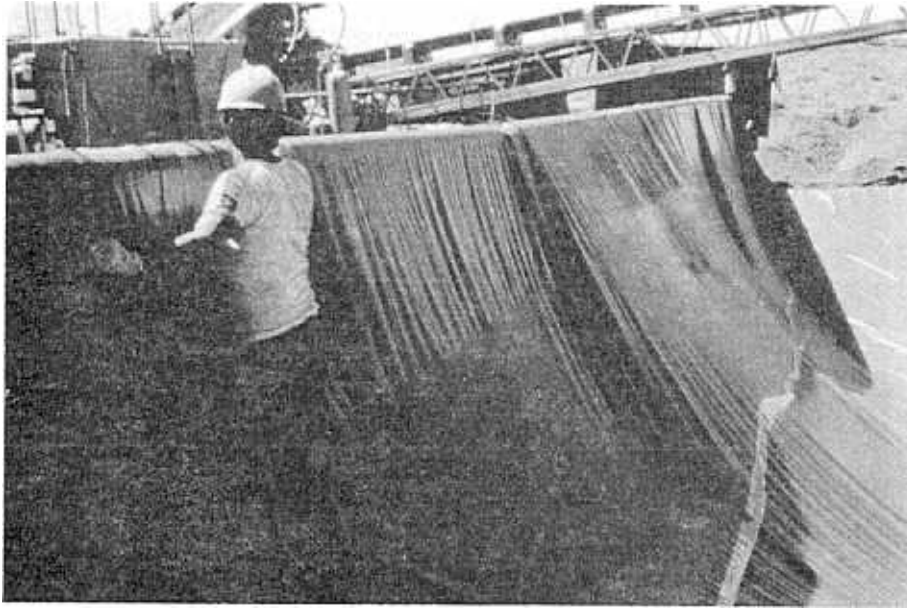


Figure 30. - View of worker adjusting slack in PVC geomembrane as it is being continually placed from the platform shown on figures 28 and 29.



Figure 31. - View of RAHCO trimmer used to place PVC/soil cover in one operation. Excavated material comes through machine to be placed on PVC as shown on figure 33.

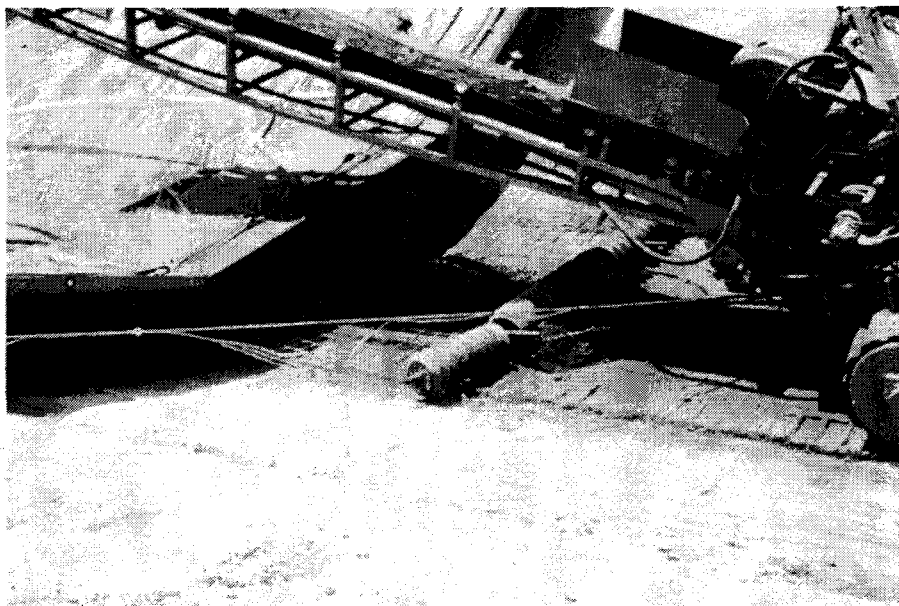


Figure 32. - View of RAHCO trimmer showing screens, rollers, etc., attached between excavator portion and PVC which are used to remove ridges and bumps prior to installation of the geomembrane and protective soil cover.

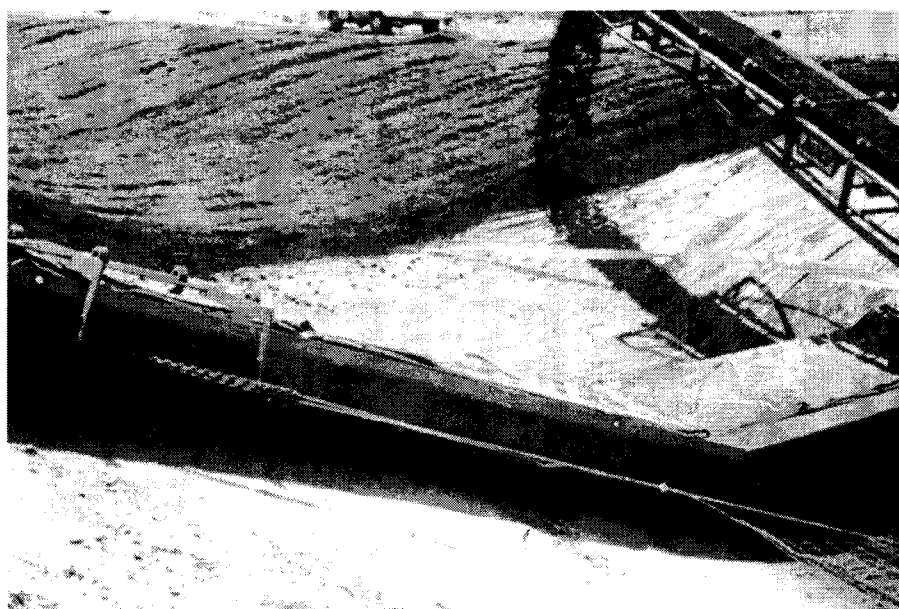


Figure 33. - View showing placement of protective soil cover as PVC geomembrane is continually being installed.



Figure 34. - Overall view showing placement of PVC geomembrane and protective soil cover.

Protective Soil Cover

The protective soil cover is placed soon after the plastic lining is installed to eliminate possible wind or other damage. The soil cover is an essential part of a buried membrane lining system because its function is to protect the geomembrane from the elements, animal traffic, vandalism, and mechanical damage during canal cleaning operations.

The soil material used should be obtained from approved areas. The inclusion of rocks, boulders, vegetable matter, brush, large roots, and other objectionable foreign matter is not permitted. Also, soil cover should not be placed when it is frozen or contains frozen material.

Proper placement of the cover material is important to avoid puncturing, tearing, or stressing of the geomembrane. Consequently, good inspection is required during this construction procedure to ensure that no damage occurs to the geomembrane.

The cover material can be placed with backhoes, conveyors, or by other approved means, preferably starting at the toe and working upslope. Draglines may then be used to groom the surface. Various methods for placing the cover are shown on figures 35 through 38. Cover material should not be dropped on the liner from heights in excess of 0.9 m (3 ft). Also, the cover material should not be placed when the surface temperature of the geomembrane is below 2 °C (35 °F) unless the contractor can demonstrate that no damage will occur at these temperatures.

The canal invert should be covered first. Small dozers with large flotation tracks can be used to spread the soil cover in the canal invert, providing equipment stays on the cover material and a sharp turning radius is avoided.



Figure 35. - Placement of protective soil cover using dragline. Good inspection is required during this construction procedure to avoid damage to the geomembrane. The soil cover should not be dropped from heights greater than 0.9 m (3 ft).



Figure 36. - Another view showing placement of soil cover using dragline. A grade-all is spreading cover material on side slopes. The material should be placed from the toe working up slope to avoid dislodging and damaging the geomembrane.



Figure 37. - Spreading cover material on side slopes. Contractor has welded steel plate to the bucket.

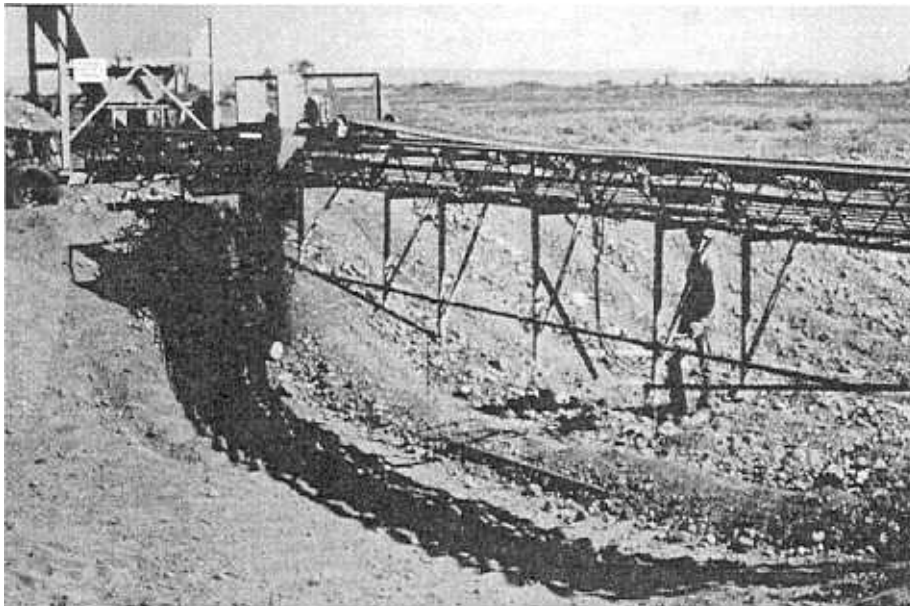


Figure 38. - View of conveyor system used to place sand/gravel cover. Material is placed in a windrow fashion and will have to be dragged in to finish condition as shown on figure 39.



Figure 39. - View of completed canal section with buried geomembrane.

To reduce construction costs, the protective soil cover is not compacted, but only dragged to produce a uniform and trim condition. Figure 39 shows a typical section of a finished canal.

Cover soil that has marginal gradation characteristics may require consolidation to improve stability. In this case, the material on the bottom of the canal should be placed and consolidated prior to the material on the side slopes. A 4-foot-wide, smooth cylindrical roller, weighing not less than 50 pounds per linear inch when fully loaded, should be passed at least twice over the surface area.

O&M CONSIDERATIONS

The following items may be of interest in the operation and maintenance of canals with buried geomembranes:

1. When the protective soil cover is not compacted, some consolidation and settlement of the material will likely occur soon after the canal is placed in service. This process will often require minor repairs to the cover material.
2. As a result of the low water velocities (less than 3.0 feet per second) associated with buried geomembranes, some silt deposits may occur which will necessitate periodic removal. When cleaning canals, it is very important that the equipment operators are aware of the type of linings being cleaned in order to avoid damaging the geomembrane. In some areas, additional access roads may have to be built to allow the use of backhoes or grade-alls for cleaning.
3. Weeds have not presented a problem in lining new canals because the majority of weeds, seeds, and root systems are removed during the excavation process. However, precautionary measures are required when geomembrane is constructed in existing canals where the subgrade is infested with cattails, tules, willows, johnson grass, nut grass, or other deep-rooted growths. The growth should be grubbed and the soil should be treated with an approved sterilant. Weeds growing in the cover material are generally not expected to cause damage to the geomembrane; however, roots of the more vigorous plants, such as willow, can penetrate the membrane. An effective weed control program will minimize this problem.
4. Rodents have not presented any major problems to buried geomembranes. The Animal and Plant Health Inspection service of the U.S. Department of Agriculture, in cooperation with Reclamation, has prepared a publication (Hegdal and Harbour, 1991) on the "Prevention and Control of Animal Damage to Hydraulic Structures."
5. O&M roads should be constructed and maintained to prevent surface runoff from eroding the protective soil cover on the canal slope. Roads should be sloped so that rain water flows away from the canal. Such erosion damage is shown on figure 40.
6. Canals should be fenced in areas where deer, antelope, or livestock might be present.

At the present time, Designer's Operating Criteria for buried geomembrane have not yet been developed. However, several irrigation districts have furnished (Bureau of Reclamation, 1984b) the following guidelines for filling and dewatering:

Midvale Irrigation District, Wyoming

Filling - Done gradually to flush the system and depends on wasteway capacities, reach lengths between wasteways, and types of control structures. About 15 percent of the design capacity is brought into the system initially. Most of this flow is progressively wasted through the next downstream wasteway to flush the system. Check boards are installed in order to flush debris from higher elevations in the canal prism in a similar manner. Following flushing, flow is gradually increased to meet irrigation demands.



Figure 40. - View showing erosion of soil cover from surface runoff. O&M roads should be constructed and maintained to prevent this type of erosion problem.

Dewatering - Initial drop in canal water level should not exceed 15 percent of total depth. Check boards are removed to reduce flow in increments of about 25 percent for the remaining depth.

Helena Valley Irrigation District, Montana

Filling - Canals with capacity ranges of 300 to 500 ft³/s are filled in about 50 ft³/s increments for flushing and to meet demands.

Dewatering - Canals are drained slowly, corresponding to reduced irrigation demands.

East Bench Irrigation District, Montana

Filling - East Bench Main Canal, $Q = 440 \text{ ft}^3/\text{s}$. About 10 percent of design capacity (or 50 ft³/s) is turned into canal for flushing purposes. Flow is maintained at this rate for about 2 days. Canal is then checked to slow travel and allow District personnel time to work ahead of the water. After initial flushing, flow is increased to 100 ft³/s to enable delivery to laterals for initial flushing and subsequent deliveries. Flow is gradually increased to design capacity.

Dewatering - Flow is gradually reduced to 100 ft³/s (approximately 75 percent of design capacity) as demand drops. Flow is then reduced from 100 to 0 ft³/s in 2 stages. Check boards are left in place and canal gradually allowed to drain by leakage between check boards, generally over a period of 2 weeks.

During a past emergency situation, flow was reduced instantly by 25 percent (approximately 110 ft³/s). No problems with lining developed as a result of rapid drawdown.

CANAL FIELD STUDIES

General

An ongoing study is being conducted to evaluate the performance of various geomembranes, e.g., PVC, VLDPE, HDPE, CSPE, PP, etc. The study, conducted initially under the OCCS program and then under Water Research NM026 and NM092, involves both field and laboratory evaluations. The field evaluation includes:

1. Obtaining samples of in-service lining for laboratory evaluation.
2. Making visual observations concerning the condition of the in-service lining and protective earth cover material.

The laboratory evaluation of the retrieved samples involves:

1. Visual examination.
2. Physical properties testing.
3. Conducting chemical extraction tests to determine plasticizer content of the PVC lining. The method used for this determination is discussed under "Laboratory Studies."

The geomembrane installations are discussed on an individual basis in the following paragraphs; background information on each installation is also included. The hydraulic properties of the canal installations evaluated in this report are listed in table 5.

Table 5. - Typical hydraulic properties of geomembrane-lined canals and laterals.

Feature	Flow		Velocity		slope	s:s	Bottom Width		Normal Water Depth	
	m ³ /s	ft ³ /s	m/s	ft/s			m	ft	m	ft
Helena Valley Canal	4.25	150	0.64	2.10	0.00035	2:1	2.7	9.0	1.28	4.19
East Bench Canal	11.47	405	.059	1.95	0.00013	2:1	6.1	20.0	1.96	6.44
Bugg Lateral	2.66	94	0.57	1.86	0.00035	2:1	2.4	8.0	1.04	3.40
Fivemile Lateral	1.81	64	0.68	2.22	0.00082	2:1	3.0	10.0	0.66	2.15
Farwell Main Canal	10.75	380	0.65	2.12	0.00017	2:1	6.1	20.0	1.74	5.70
Farwell Lower Main Canal	2.26	80	0.48	1.58	0.00025	2:1	2.7	8.8	1.00	3.30
New Rockford Canal										
Reach 1A	44.80	1,600	0.72	2.37	0.00007	2:1	13.4	44.0	3.17	10.40
Reach 2	44.80	1,600	0.70	2.31	0.00007	2.5:1	12.2	40.0	3.19	10.45
South Canal										
VLDPE lined	7.00	250	-	-	0.0008	2.5:1	3.7	12.0	1.46	4.80
PO composite	10.08	360	-	-	0.00027	1.5:1	6.1	20.0	1.62	5.30
Mirdan Canal	24.36	870	0.83	2.71	0.000096	1.5:1	4.0	13.0	3.32	10.90

Helena Valley Canal, Helena Valley Unit, Montana

In the fall and winter of 1968-69, a 1930-m (6332-ft) reach of the Helena Valley Canal was lined with 0.25-mm (10-mil) thick PVC geomembrane. This project was the first PVC lining installation under a Bureau construction specification (Bureau of Reclamation, 1968). The PVC was furnished in sheets 12.8 m (40 ft) wide by 122 m (400 ft) in length. After completion of the work the Reclamation Office in Great Falls, Montana, prepared a comprehensive report on the installation (Bureau of Reclamation, 1969).

Samples were obtained by field personnel in the spring of 1974 and submitted to the Denver Office for testing and evaluation (Bureau of Reclamation, 1974). Ponding tests were conducted in October 1973 and again in April 1974 to determine seepage losses. The results of the ponding tests are as follows:

Location	Date	Water Loss	
		(L/m ²)/day	(ft ³ /ft ²)/day
Station 1321+92 to	Oct. 07-08, 1983	14.33	0.047
1377+58	April 25-26, 1974	16.76	0.055

Seepage values agree with accepted values of 0.07 ft³/ft²/day for concrete lined canals. Field personnel attribute the lower water losses in the fall to the higher ground water table which occurs that time of the year. In any event, both 0.05 and 0.06 are very low values.

In November 1977, an inspection was made on the Helena Valley canal lining. A small area of the lining at station 1330+60 was uncovered for examination and sampling (Morrison, 1977). The lining appeared to be in good condition, and a sample was obtained for laboratory evaluation. The subgrade was fairly smooth, with no protruding aggregate, and the sand/gravel cover appeared to be stable. The depth of cover was about 430 mm (17 in).

During the 1977 inspection, the performance of the PVC lining was discussed with field personnel. In their opinion, the plastic was performing satisfactorily. Growth of pond weeds and a recent infestation of Russian Olive had created some minor maintenance problems. Also, at several locations, cattle had disturbed the sand/gravel cover and damaged the membrane. The most damage occurred at station 96+30, where heavy animal traffic had crossed the canal in a path 6 to 9 m (20 to 30 ft) wide.

Samples were again obtained in the spring of 1984 after 15 years of service (figs. 41 to 46), and again in 1989 after 21 years of service. The results of laboratory tests conducted on all retrieved samples are summarized in tables 6 and 7.

Results of the physical properties tests indicate that the lining is continuing to age and stiffen as noted by the increasing tensile strength coupled with decreasing elongation properties. The lining thickness has also decreased with time. In addition, the impact resistance continues to decrease as evidenced by the results of the Elmendorf Tear Test (ASTM: D-1922). The lower impact resistance was also observed in the samples retrieved after 21 years of service as evidenced by apparent shattering of the geomembrane caused by animal traffic. The impact damage is shown on figures 47 and 48.

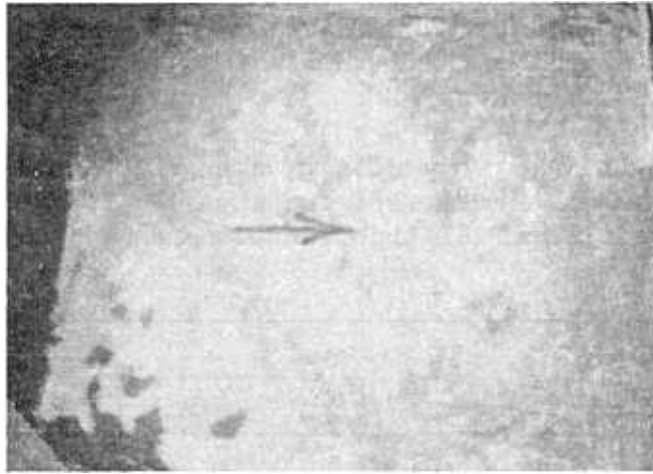


Figure 41. - View of exposed PVC membrane lining (sample No. 21418) at station 1330+00, below waterline. Photograph taken spring 1984. Helena Valley Canal, Montana.



Figure 42. - Close-up view of exposed PVC membrane lining at station 1330+00, below waterline. Photograph taken spring 1984.

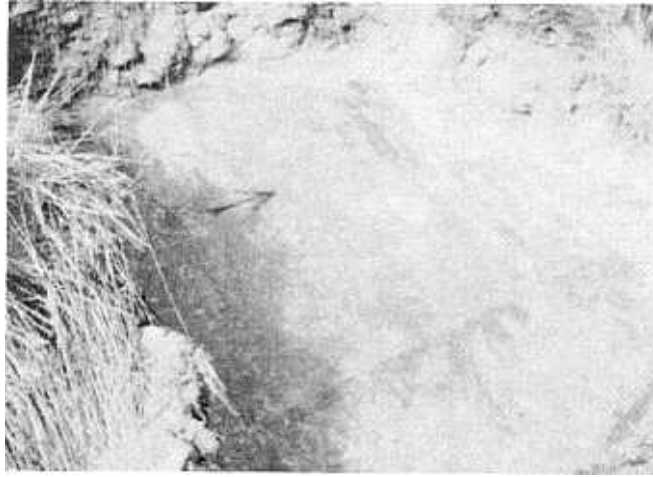


Figure 43. - View of exposed PVC membrane lining (sample No. 21419) at station 1330+00, above waterline. Photograph taken spring 1984. Helena Valley Canal, Montana.

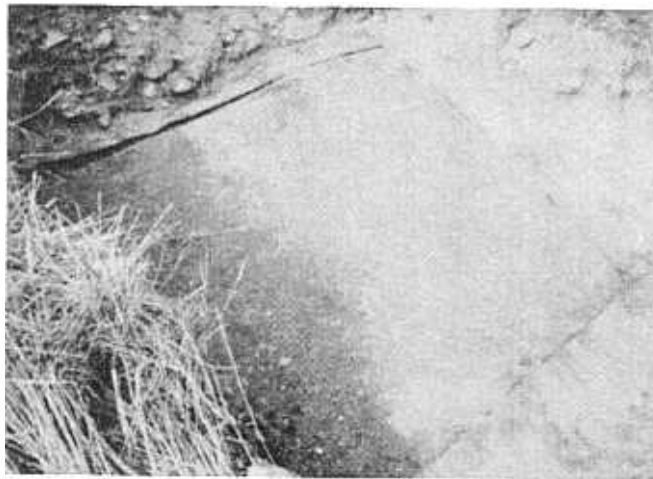


Figure 44. - View of subgrade at station 1330+00, above waterline. Photograph taken spring 1984. Helena Valley Canal, Montana.

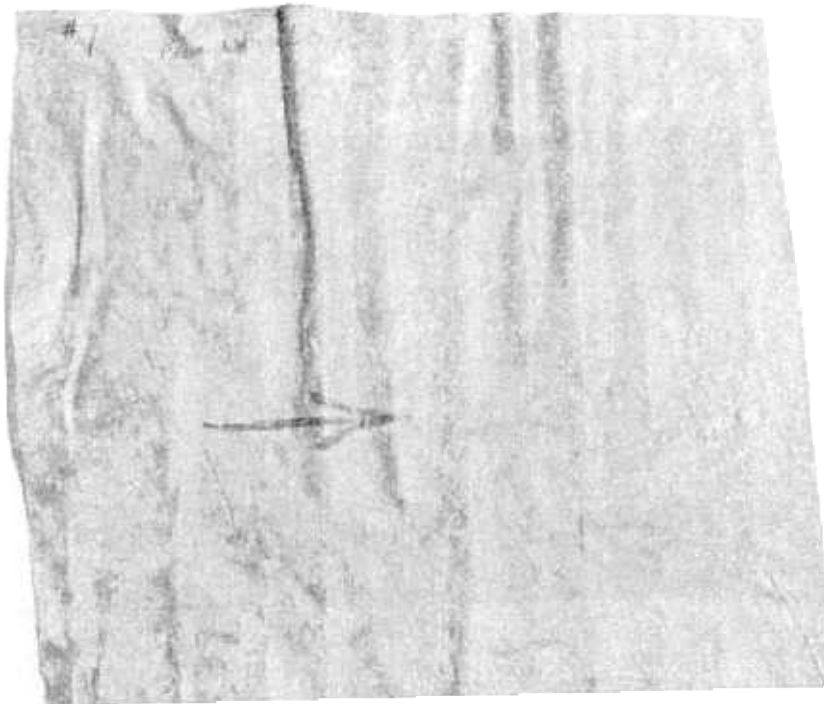


Figure 45. - View of 15-year-old field sample No. 21418.

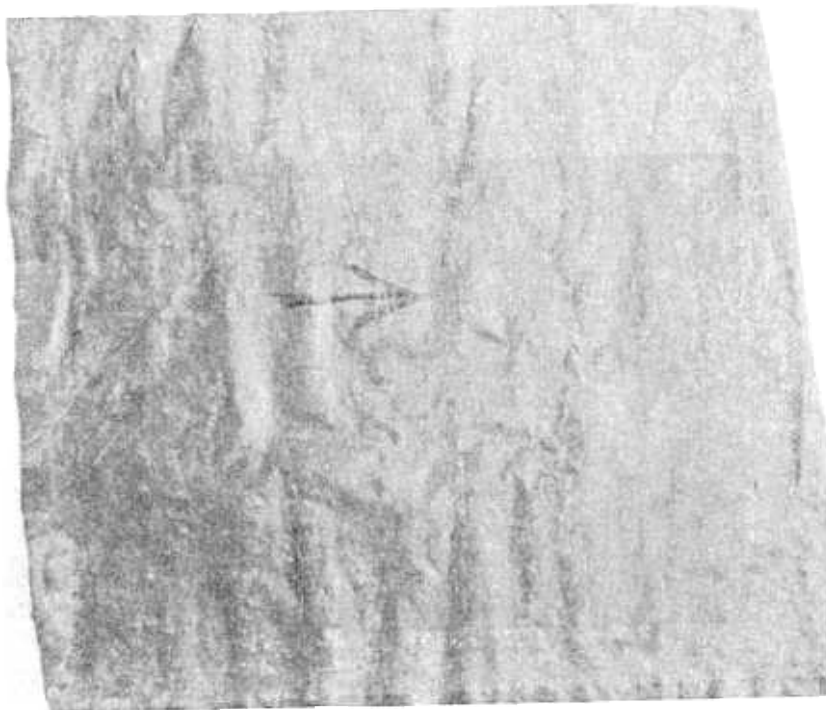


Figure 46. - View of 15-year-old field sample No. 21419.

Table 6. - Results of visual examination of PVC membrane lining samples from Helena Valley Canal, Helena Valley Unit, Montana.

Laboratory sample No.	Service life (yrs.)	Location in canal	Sample size		Remarks
			(m ²)	(yd ²)	
B-6666	5.3	Sta. 1322+33, from within water prism	0.84	1.00	Sample obtained from an area where the lining had been placed over a fairly smooth subgrade.
B-6667	5.3	Sta. 1322+33, from above high waterline	0.84	1.00	Sample slightly stiffer than B-6666. Same type of subgrade conditions as noted for B-6666.
B-6874	9.0	Sta. 1330+60, from within water prism	0.56	0.67	Sample fairly flexible; contained 1 shovel tear, 7 aggregate tears, and 17 pinholes.
21418	15.0	Sta. 1330+00, from within water prism	0.68	0.81	Very little difference noted in stiffness between this sample and 21419. Sample contained 12 pinholes and 3 small tears due to protruding aggregate in the subgrade.
21419	15.0	Sta. 1330+00, from above high waterline	0.84	0.70	Sample was stained a brownish color in upper portion. Sample contained two pinholes and had a factory seam.
22975	21.0	Sta. 1330+00, from within water prism	0.79	0.94	There is some evidence of shattering of the sample from animal traffic. Sample had numerous pinholes and tears and contained a factory seam.
22976	21.0	Sta. 1330+00, from above high waterline	0.86	1.03	As with 22975, this sample also exhibited some shattering from being subjected to animal traffic. It also contained numerous pinholes and tears. Some rust color was observed in the side of the sample away from the subgrade.

Table 7. - Physical properties test results for PVC membrane linings, Helena Valley Canal, Specifications No. 604C-72, installed fall and winter 1968-69.

Physical property	Specifications requirements	Sample No. B-5716 (original)	Sample No. B-6666 (5.3 years of service, BWL)	Sample No. B-6667 (5.3 years of service, AWL)	Sample No. B-6874 (9 years of service, BWL)	Sample No. 21418 (15 years of service BWL)	Sample No. 21419 (15 years of service, AWL)	Sample No. 22975 (21 years of service, BWL)	Sample No. 22976 (21 years of service, AWL)
Thickness, mm (mils)	0.25 (10) ±10	0.27 (10.8)	0.26 (10.1)	0.25 (9.8)	0.26 (10.2)	0.25 (9.9)	0.25 (9.9)	0.24 (9.4)	0.23 (8.8)
percent change			-5.9	-9.1	-5.5	-8.0	-8.1	-13.0	-18.5
Tensile strength, N/mm (lbf/in)	*3.0 (17)	5.4 (30.6) L	4.1 (23.5) L	4.1 (24.8) L	6.1 (34.6) L	6.6 (37.5) L	6.2 (35.5) L	6.4 (36.3) L	6.0 (34.2) L
percent change		5.8 (33.3) T	4.5 (25.5) T	4.0 (23.0) T	5.0 (28.7) T	5.6 (32.0) T	5.7 (32.5) T	5.0 (28.3) T	5.4 (30.5) T
			-23.3 L	-19.0 L	+13.1 L	+22.5 L	+16.0 L	+18.6 L	+11.8 L
			-23.4 T	-30.9 T	-13.8 T	-3.9 T	-2.4 T	-15.0 T	-8.4 T
Elongation percent, percent change	*225	353 L	190 L	179 L	180 L	200 L	180 L	172 L	181 L
		348 T	326 T	201 T	225 T	208 T	220 T	185 T	213 T
			-46.2 L	-49.3 L	-49.0 L	-43.3 L	-49.0 L	-51.2 L	-48.7 L
			-6.3 T	-42.2 T	-35.3 T	-40.2 T	-36.8 T	-46.8 T	-38.9 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.4 (13.9) L	3.2 (18.5) L	3.7 (20.9) L	4.8 (27.2) L	5.5 (31.5) L	5.4 (31.0) L	5.8 (32.9) L	5.3 (30.2) L
percent change		2.2 (12.8) T	2.4 (13.9) T	3.2 (18.1) T	3.7 (21.4) T	4.7 (27.0) T	4.8 (27.5) T	5.0 (28.4) T	4.7 (26.8) T
			+33.1 L	+50.4 L	+95.7 L	+126.6 L	+123.0 L	+136.7 L	+117.3 L
			+8.6 T	+41.4 T	+67.2 T	+110.9 T	+114.8 T	+121.9 T	+109.4 T
Elmendorf Tear, gm percent change	*1500	2590 L	2750 L	3000 L	1825 L	750 L	807 L	420 L	490 L
		2200 T	3145 T	3905 T	3490 T	1290 T	1470 T	740 T	1015 T
			+6.2 L	+15.8 L	-29.5 L	-71.0 L	-68.8 L	-83.8 L	-81.1 L
			+42.9 T	+77.5 T	+58.6 T	-41.4 T	-33.2 T	-66.4 T	-53.9 T
Graves tear, N (lbf)	Not required	Not determined	Not determined	Not determined	Not determined	24.5 (5.5) L	27.1 (6.1) L	24.5 (5.5) L	24.9 (5.6) L
						28.9 (6.5) T	32.9 (7.4) T	27.6 (6.2) T	25.8 (5.8) T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18 °C (0 °F)	10 tested, 0 failures	5 tested, 0 failures	5 tested, 5 failures	Not determined	5 tested, 5 failures	5 tested, 5 failures	Not determined	Not determined
Bonded Seam strength in shear, N/mm (lbf/in)	2.6 (15)	4.4 (24.8)	No sample	No sample	4.8 (27.0)	No sample	5.1 (29.0)	4.9 (28.0)	No sample
Bonded seam strength in peel, N/mm (lbf/in)	Not required	No sample	No sample	No sample	No sample	No sample	3.7 (21.0)	No sample	No sample
Plasticizer content, percent change	Not required	37.5	31.8	26.8	24.6	20.9	20.5	17.3	17.5
			-15.2	-28.5	-34.4	-44.3	-45.3	-53.9	-53.3

T denotes transverse direction; L denotes longitudinal direction ; * Minimum, each direction; AWL denotes above normal waterline; BWL denotes below normal waterline.



Figure 47. - View of 21-year-old field sample (22975) obtained from below waterline near station 1330+00, Helena Valley Canal, Montana. Sample has suffered some damage from animal traffic.



Figure 48. - View of 21-year-old field sample (22976) obtained from above waterline. As with sample shown on figure 47, it has also suffered damage from animal traffic.

The changes in these physical properties are primarily caused by partial loss of plasticizer (the agent used in PVC compounds to impart flexibility) through migration, volatilization, or chemical change. Chemical extraction tests showed about a 54-percent loss in plasticizer for the 21-year-old field sample.

During the 1989 sampling, the irrigation district personnel reported that the sample site above the waterline had about 0.2 m (8 in) of gravelly sand cover, and the sample site located within the water prism had about 0.3 m (12 in) of the same type of cover material. The subgrade material beneath the sampled sites was a packed sand in good, smooth condition. Field personnel also reported that although livestock in some areas has caused damage, the lining is still providing satisfactory seepage control after 21 years of service (Foster, 1977).

East Bench Canal, East Bench Unit, Montana

Between 1961 and 1971, the following quantities of asphalt and plastic membrane linings were installed on the East Bench Canal Near Dillon, Montana.

Number of Contracts	Membrane Material	Length		Area	
		ft	m	yd ²	m ²
7	Asphalt	236,680	72,140	1,020,000	852,850
2	10-mil PVC	25,350	4,680	113,950	95,280

Samples evaluated in this study came from the first PVC installation on the East Bench Canal accomplished in the fall and winter of 1969-70 under Specifications No. 604C-77. At the completion of the installation, an excellent report covering the construction was prepared by the Reclamation office in Great Falls, Montana (Bureau of Reclamation, 1970).

Photographs taken during the October 1983 inspection, when the 14-year-old field samples were retrieved, are shown on figures 49 through 56. Laboratory photographs of the retrieved samples are shown on figure 57 and 58.

Samples of the 0.25-mm (10-mil) PVC lining were obtained for evaluation after 4, 5, 8, and 14 years of service. Laboratory test results are summarized in tables 8, 9a, 9b, and 9c. Results of these tests indicate that, as with the Helena Valley Canal, the lining is continuing to stiffen with time. However, in comparing the results between 8 and 14 years of service, the rate of stiffening or aging appears to have decreased. Very little change in physical properties has occurred during the 6-year interim. Also, results of shear and peel tests conducted on a 14-year-old factory seam sample indicated that it was in good condition with no apparent deterioration.

Chemical extraction tests indicated a plasticizer content of 18.5 percent (by weight) and 20.5 percent for 14-year-old samples. On the basis of the original plasticizer content of 33.2 percent, the plasticizer content was 44 percent and 38 percent lower. This result compared to a 37 percent loss for the 8-year-old sample taken from the same location. Therefore, it appears that very little plasticizer loss has occurred between 8 and 14 years of service. The loss of plasticizer with time is shown on figure 59.

The following quotation is excerpted from the East Bench Irrigation District Manager's letter report (Kennedy, 1983) prepared after the 1983 inspection:

"Both samples were taken within the water prism as the specifications for the installation of the membrane lining provided for lining approximately 1.0 ft above the design water surface. Without exception, during periods of high water demand the depth of water exceeded the design depth. We would certainly recommend that future lining be at least 18 inches above design water depth if not greater.

"The lining in place was in excellent condition with no holes or tears. The tears in the samples are a result of not exercising enough care when removing the cover material.



Figure 49. - East Bench Canal looking downstream from station 900+00 showing general condition of the canal in the vicinity of where PVC lining samples were taken. Photograph taken October 20, 1983.



Figure 50. - East Bench Canal looking upstream from station 900+00. Sand and gravel cover in excellent condition. Cover depth was about 20.5 mm (18 in). Photograph taken October 20, 1983.



Figure 51. - Closer view of cover material at station 902+25 where samples of PVC lining were taken.



Figure 52. - View of exposed upper lining sample No. 21211 showing lining, depth, and condition of cover material. Station 902+25. Photograph taken October 20, 1983.

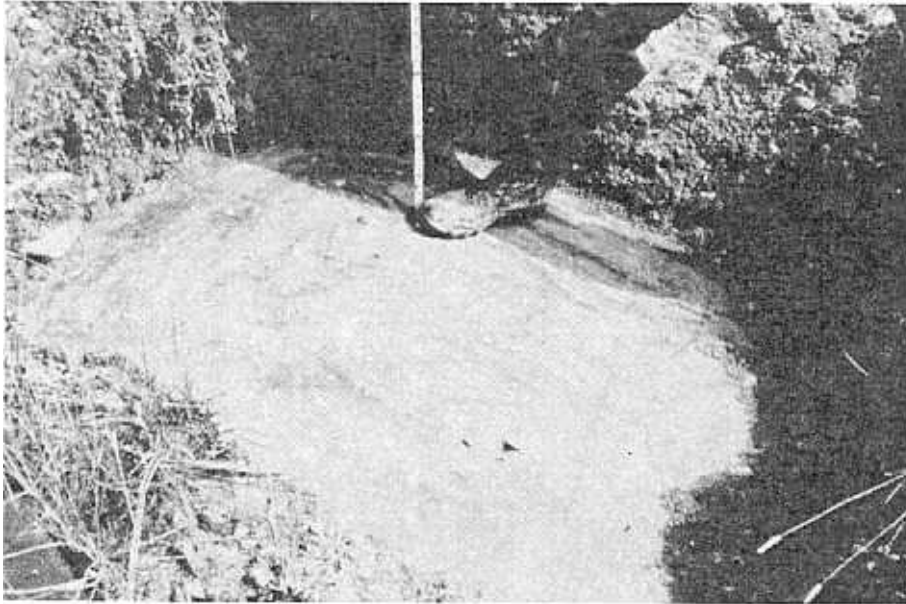


Figure 53. - Close-up view of upper lining sample No. 21211. Tears in lining were a result of removing cover material during sampling. Photographs taken October 20, 1983.

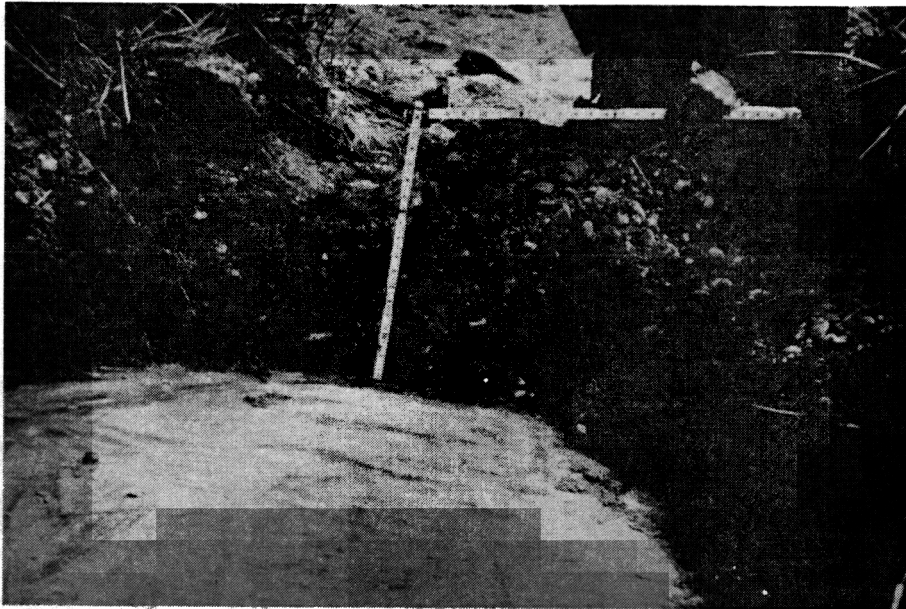


Figure 54. - View of exposed upper lining sample again showing depth of cover material. Station 902+25. Photograph taken October 20, 1983.

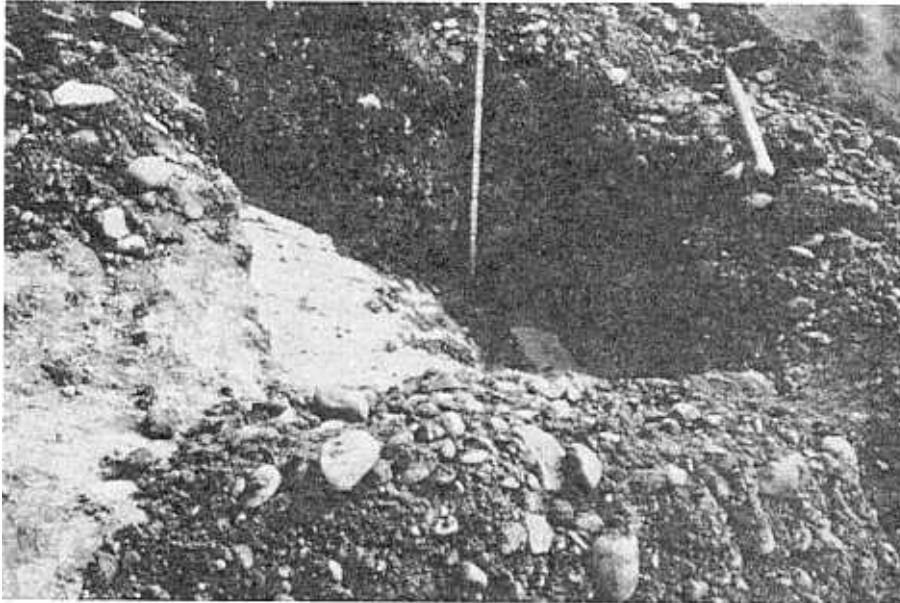


Figure 55. - View of exposed lower lining sample No. 21210 showing depth and condition of cover material.

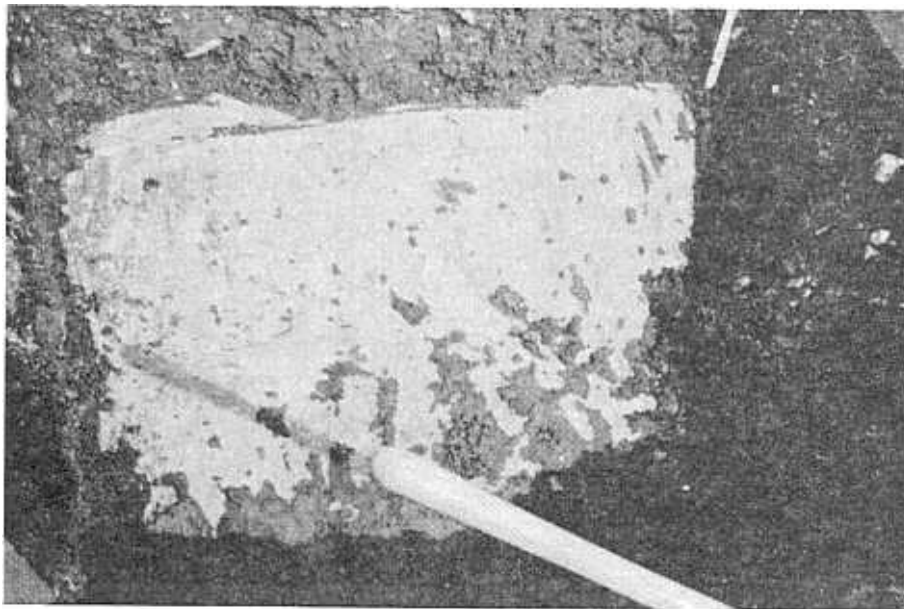


Figure 56. - Close-up view of exposed lower lining sample No. 21210 in place, depth, and condition of cover material. Station 902+25. Photograph taken October 20, 1983.



Figure 57. - View of 14-year-old field sample No. 21210.

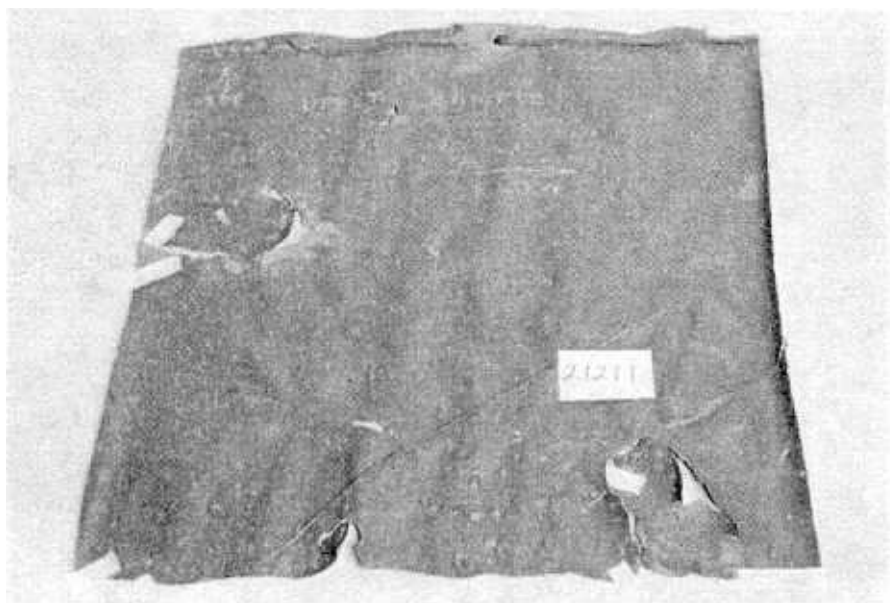


Figure 58. - View of 14-year-old field sample No. 21211.

Table 8. - Results of visual examination of PVC membrane lining samples from East Bench Canal, East Bench Unit, Montana.

Laboratory sample No.	Service life (yrs.)	Location in canal	Sample size (m ²) (yd ²)		Remarks
B-6668	4.3	Sta. 900+80, from above high waterline	0.84	1.00	Both samples B-6668 and B-6669 were stiffer than those obtained from Helena Valley Canal. They also suffered more damage from subgrade aggregate.
B-6669	4.3	Sta. 900+80, from within water prism	0.84	1.00	
B-6752	5.0	Sta. 904+30, from above high waterline	1.11	1.13	Sample contained 1 large tear from shovel during sampling and 25 small tears from contact with protruding subgrade aggregate.
B-6753	5.0	Sta. 904+30, from within water prism	1.16	1.39	Sample slightly stiffer than B-6752; appeared to come from an area where lining had been placed over a smooth subgrade. Sample contained 7 tears and 2 pinholes.
B-6872	8.0	Sta. 1353+60, from within water prism	0.56	0.67	Sample contained small tears from contact with protruding subgrade aggregate and 27 pinholes.
B-6873	8.0	Sta. 906+15, from within water prism	0.56	0.67	2 diagonal tears during sampling; Sample contained 28 pinholes.
21210	14.0	Sta. 902+25, from within water prism	0.84	1.00	Sample somewhat stiff. It had a "marbled" appearance due to varying shades of its gray color. Sample contained 4 tears from shoveling during cover removal, 4 holes about 0.5-in. (13-mm) from contact with protruding aggregate, and 14 pinholes. Sample contained a factory seam.
21211	14.0	Sta. 902+25, from within water prism	0.84	1.00	Similar stiffness noted as with sample No. 21210. No "marble" appearance noted. Sample contained 4 tears from shoveling, 1 hole due to protruding subgrade aggregate, and 26 pinholes.

Table 9a. - Physical properties test results for PVC membrane linings on East Bench Canal, Specifications No. 604C-77, installed fall and winter 1969-70.

Physical property	Specifications requirements	Sample B-6007 (original)	Sample B-6668 (4.3 yr of service, AWL ¹)	Sample B-6669 (4.3 yr of service, BWL ²)	Sample B-6752 (5 yr of service, AWL)
Thickness, mm (mils), percent change	0.25 (10) ±10	0.26 (10.2)	0.24 (9.3) -8.8	0.24 (9.6) -5.9	0.24 (9.4) -7.8
Tensile Strength, N/mm (lbf/in), percent change	*3.5 (20)	5.6 (31.9) L ³ 4.9 (28.0) T ⁴	5.2 (29.7) L 4.6 (26.4) T -6.9 L -5.7T	4.6 (26.3) L 3.7 (21.1) T -17.6 L -24.6T	5.2 (29.6) L 5.0 (28.7) T -7.2 L +2.5 T
Elongation, percent change	*250	312 L 334 L	105 L 92 T -66.3 L -72.5 L	149 L 128 T -52.2L -61.7T	153 L 208 T -51.0 L -37.7 T
Modulus at 100 percent elongation, N/mm (lbf/in), percent change	Not required	2.8 (16.0) L 2.4 (13.9) T	5.1 (29.2) L Not determined +82.5 L Not determined	4.1 (23.6) L 3.4 (19.7) T +47.5 L +41.7 T	4.7 (26.7) L 4.2 (23.8) T +66.9 L +71.2 T
Elmendorf Tear, grams, percent change	*1600	2622 L 3022 T	1265 L 2615 T -51.8 L -13.5 T	2450 L 4070 T -6.6 L +34.7 T	1440 L 1760 T -45.1 L -41.8 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18°C (0 °F)	10 tested 0 failures	5 tested 5 failures	5 tested 5 failures	5 tested 5 failures
Plasticizer content, percent percent change	Not required	33.2	20.4 -38.6	25.3 -23.8	22.5 -32.2

¹AWL denotes above normal waterline.

²BWL denotes below normal waterline.

³L denotes longitudinal direction.

⁴T denotes transverse direction.

*minimum, each direction

Table 9b. - Physical properties test results for PVC membrane linings on East Bench Canal, Specifications No. 604C-77, installed fall and winter 1969-70.

Physical Property	Specifications Requirements	Sample No. B-6753 5 yr of service BWL ¹	Sample No. B-6872 8 yr of service BWL	Sample No. B-6873 8 yr of service BWL
Thickness, mm (mils), % change	0.25 (10) ±10	0.24 (9.6) -5.9	0.24 (9.5) -6.9	0.23 (9.2) -9.8
Tensile Strength, N/mm (lbf/in), % change	*3.5 (20)	5.0 (28.8) L ² 4.7 (27.1) T ³ -9.7 L -3.2 T	5.1 (29.3) L 4.9 (27.8) T -8.2 L -0.7 T	4.8 (17.7) L 4.7 (27.0) T -13.2 L -3.6 T
Elongation, % change	*250	156 L 193 T -50.0 L -42.2 T	148 L 180 T -52.6 L -46.1 T	109 L 175 T -65.1 L -47.6 T
Modulus at 100% elongation, N/mm (lbf/in) % change	Not Required	4.5 (25.8) L 4.0 (23.0) T +61.2 L +65.5 T	4.7 (26.9) L 4.1 (23.7) T +68.1 L +70.5 T	4.7 (27.1) L 4.2 (23.8) T +69.4 L +71.2 T
Elmendorf Tear (gm) % change	*1600	2225 L 3140 T -15.1 L -3.9 T	1200 L 2175 T -54.2 L -28.0 T	790 L 1060 T -69.9 L -64.9 T
Impact Resistance	Not more than 2 specimens out of 10 shall fail at -18°C (0 °F)	5 tested 5 failures	Not determined	Not determined
Plasticizer content, % % change	Not required	22.6 -31.9	21.7 -34.6	20.9 -37.0

¹BWL denotes below normal waterline.

²L denotes longitudinal direction.

³T denotes transverse direction.

*minimum, each direction.

Table 9c. - Physical properties test results for PVC membrane linings on East Bench Canal, Specifications No. 604C-77, installed fall and winter 1969-70.

Physical property	Specifications requirements	Sample No. 21210 (14 yr of service, BWL ¹)	Sample No. 21211 (14 yr of service, BWL)
Thickness, mm (mils), percent change	0.25 (10) +10%	2.33 (9.2) -9.8	2.29 (9.0) -11.8
Tensile strength, N/mm (lbf/in), percent change	*3.5 (20)	6.0 (34.1) L ² 5.5 (31.5) T ³ +6.9 L +12.5 T	5.6 (31.8) L 5.3 (30.2) T 0 L +7.9 T
Elongation, percent change	*250	140 L 205 T -55.1 L -38.6 T	110 L 197 T -64.7 L -41.0 T
Modulus at 100 percent elongation, N/mm (lbf/in), percent change	Not required	5.5 (31.2) L 4.9 (28.0) T +95.0 L +101.4 T	5.4 (31.0) L 4.6 (26.3) T +93.8 L +89.2 T
Elmendorf Tear, grams, percent change	*1600	570 L 640 T -78.3 L -78.8 T	570 L 915 T -78.3 L -69.7 T
Graves tear, N (lbf)	Not required	23.1 (5.2) L 26.7 (6.0) T (No original values)	21.4 (4.8) L 24.9 (5.6) T
Bonded seam strength in shear, N/mm (lbf/in), percent change	*2.6 (15) (75 percent of parent material)	5.1 (29.4) +25	No sample
Bonded seam strength in peel, N/mm (lbf/in)	Not required	3.5 (20.1) (No original values)	No sample
Plasticizer content, Percent change	Not Required	18.5 -44.3	20.5 -38.3

¹BWL denotes below normal waterline.

²L denotes longitudinal direction.

³T denotes transverse direction.

*Minimum, each direction.

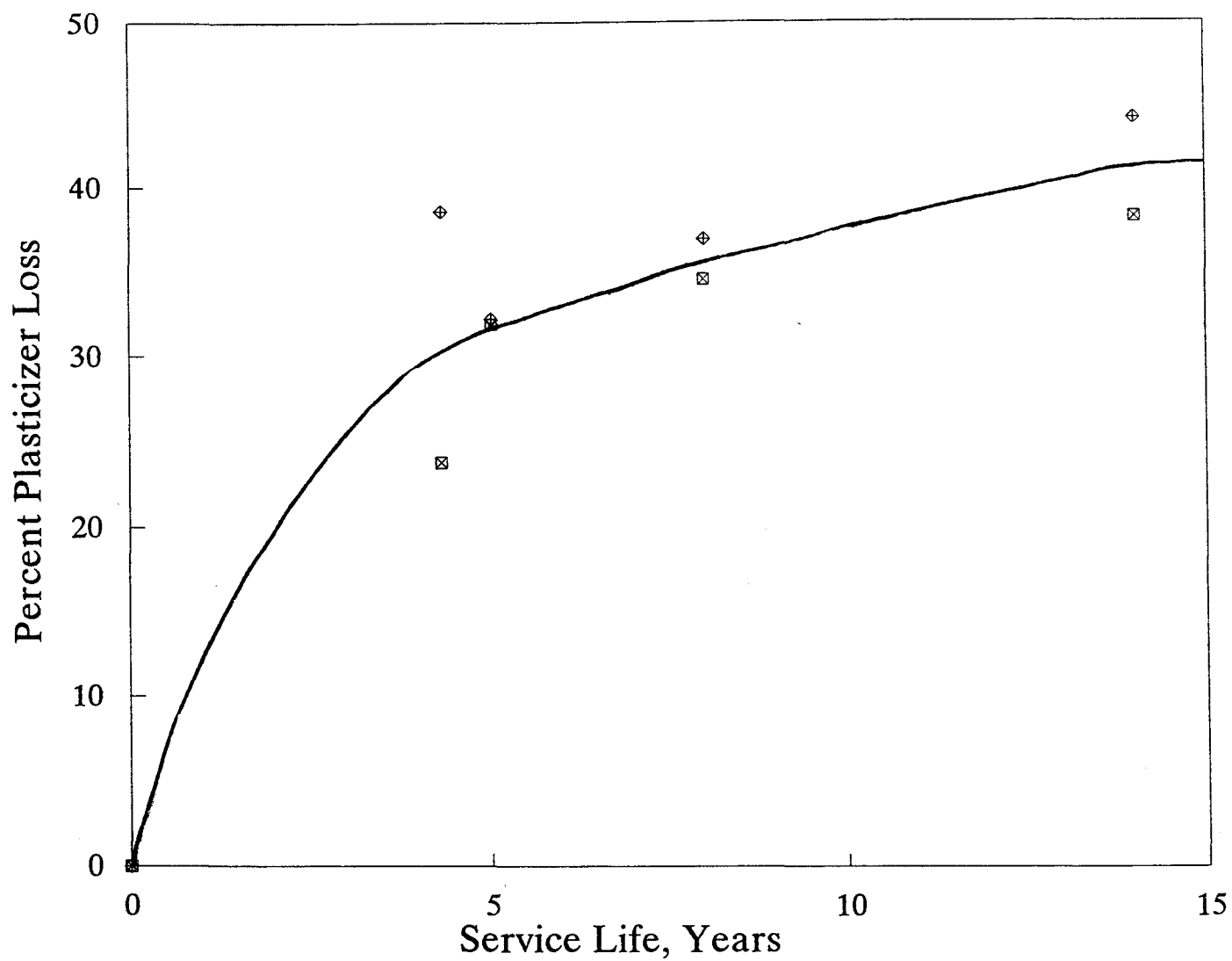


Figure 59. - Percent plasticizer loss (by weight) for PVC plastic lining samples obtained from below normal waterline on the East Bench Canal, Montana.

"As shown in the enclosed pictures, the cover material is in excellent condition. During construction we requested inspectors to require, when possible, the cover material be on the coarse side of the gradation curve. Observation of the lined sections during operation has shown that coarse cover material, if available, provides additional protection for the lining and reduces future maintenance by reducing bank erosion.

"The subgrade was also in good condition. There were several small rocks embedded in the subgrade but there were no sharp projections which pierce or break the lining. The subgrade was smooth and well compacted.

"We are pleased with the performance of the lining installed on the East Bench carriage and lateral system. Maintenance requirements for the lined sections have been negligible. With an 18 inch depth of cover material there are no problems cleaning the canal with draglines or other heavy equipment."

Ponding tests in October 1973 and April 1974 after 4 years service yielded the following:

Location	Date	Water Loss	
		(L/m ²)/d	(ft ³ /ft ²)/d
Station 878+00 to 933+61	Oct. 17-18, 1973	11.58	0.038
	April 10-11, 1974	17.07	0.056

As with the Helena Valley Canal, lower water losses occurred in the fall of the year.

Bugg Lateral, Tucumcari Project, New Mexico

In the spring of 1961, a small test section of 10-mil PVC was installed on Bugg Lateral under the LCCL Program (Ellsperman, 1961). The test section was about 228 m (750 ft) in length.

An inspection of the canal was made in 1965 and a sample was retrieved for laboratory evaluation. Results of the inspection and laboratory tests were summarized by Hickey (1969). Samples were also obtained in 1970, 1975 (Bureau of Reclamation, 1975), 1980 (Bonomo, 1980), and 1988 (Bureau of Reclamation, 1988b) after 27 years of service. Unfortunately, no field photographs were taken in 1988, but photographs taken during the 1980 field inspection are shown on figures 60 and 61. The 1980 inspection after 19 years of service indicated that the lining was intact below the waterline, but had suffered some damage from root penetration above the waterline.

Results of the laboratory tests are summarized in tables 10, 11a, 11b, and 11c. A photograph of the sample obtained in 1988 is shown on figure 62.

These results indicated that the lining is still exhibiting good elongation properties, primarily because this PVC lining was originally manufactured with a higher plasticizer content than that noted for the linings previously discussed. Also, the plasticizer used (phthalate ester) had a slightly higher molecular weight and was therefore less volatile.

Because the 27-year-old sample contained several folds as shown on figure 62, tensile tests were conducted on several specimens from the folds for comparison to those from the unfolded portion. Test results shown below indicated that the folds had no adverse effect on the tensile properties.

	Folded	Unfolded
Tensile Strength, lb/in	26.5	31.7
Ultimate elongation, %	243	216

Some additional testing on the question concerning the influence of folds on the performance of PVC is discussed under Laboratory Studies.

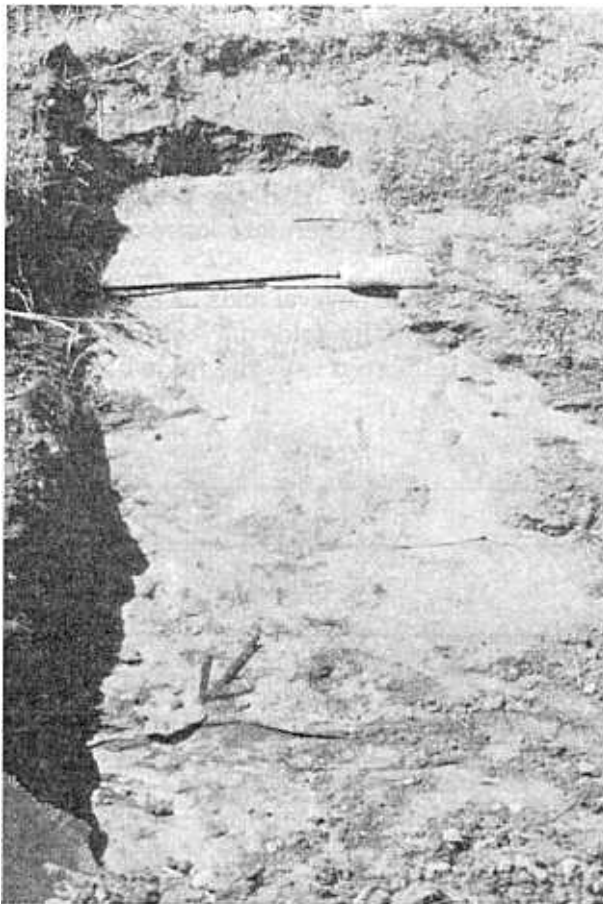


Figure 60. - View of PVC geomembrane on Bugg Lateral, Tucumcari Project, New Mexico, taken during 1980 field inspection. The geomembrane was uncovered near station 232+50 to show condition of geomembrane after 19 years of service. The broom indicates the approximate waterline. The tear shown at arrow was made by a shovel during the removal of the soil cover.

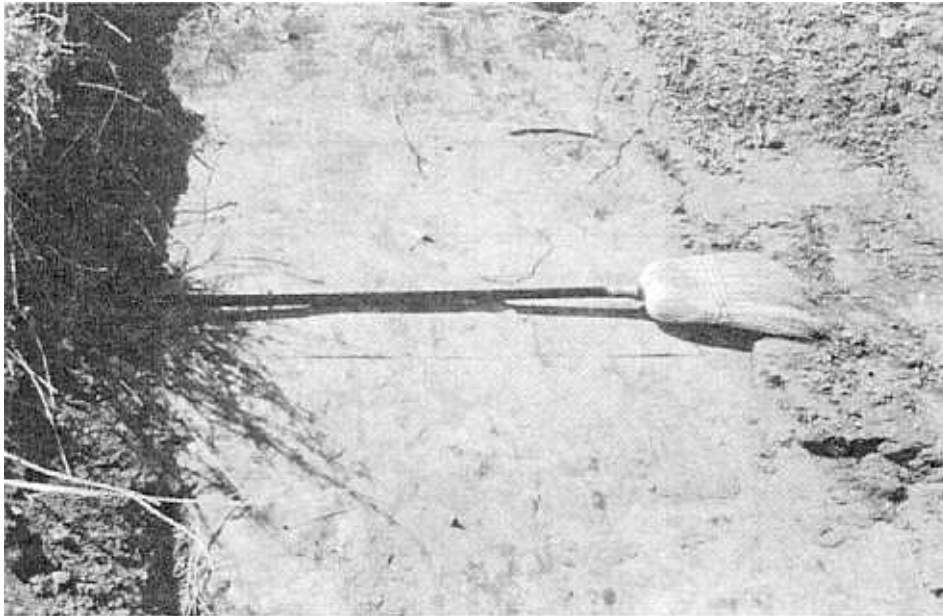


Figure 61. - Close-up view of 0.25-mm (10-mil) PVC geomembrane shown on figure 60. Note factory seam just below and running parallel to the broom. Above waterline, note the root penetration and tension tear in the upper right hand corner.



Figure 62. - View of 27-year-old field sample (22497) obtained in 1988. Sample had four folds running at a right angle to the factory seam.

Table 10. - Results of visual examination of PVC membrane lining samples from Bugg Lateral, Tucumcari Project, New Mexico.

Laboratory sample No.	Service life (yr)	Location in Canal	Sample size		Remarks
			(m ²)	(yd ²)	
B-6763	14	Sta. 229+00, from above high waterline	0.84	1.00	Sample somewhat flexible; obtained from an area where the lining had been placed over a fairly smooth subgrade. Sample contained one large hole and one large tear. Numerous pinholes noted in two general areas.
B-6764	14	Sta. 229.00+00 from within water prism	0.84	1.00	Sample in good condition: no defects noted; more flexible than B-6763.
B-7022	19	Sta. 232+50, from within water prism	1.02	1.22	Sample contained one large hole from protruding aggregate in subgrade, two tears, and nine pinholes.
B-7023	19	Sta. 232+50, from above High waterline	0.81	0.97	Sample not as flexible as B-7022; contained 98 pinholes and 8 tears.
22497	27	Unknown	0.79	0.95	Some rust color was observed in the side of the sample away from the subgrade. Sample contained two tears from aggregate. Sample contained factory seam and four folds perpendicular to the factory seam. Each fold had from 1 to 3 tears ranging in length from 12 to 75 mm (½ to 3 in.).

Table 11a. - Physical properties test results for PVC membrane linings on Bugg Lateral, Tucumcari Project, New Mexico, installed spring 1961.

Physical property	Specifications requirements	Sample No. B-3526 (Typical original results)	Sample No. B-4343 (4 yr of service, BWL)	Sample No. B-6094 (9 yr of service, BWL ¹)	Sample No. B-6763 (14 yr of service, AWL ²)
Thickness, mm (mils), percent change	0.25 (10) ±10	0.28 (11.2)	0.26 (10.2) -8.9	0.25 (9.8) -12.5	0.24 (9.3) -17.0
Tensile strength, N/m (lbf/in), percent change	*3.0 (17)	4.5 (25.6) L ³ 4.0 (22.8) T ⁴	4.8 (27.4) L 4.1 (23.7) T +7.0 L +3.9 T	4.4 (25.2) L 4.0 (22.6) T -1.6 L -0.9 T	4.6 (26.0) L 5.8 (33.3) T +1.6 L +46.0 T
Elongation, percent change	*225	412 L 462 T	322 L 336 T -21.8 L -27.3 T	260 L 433 T -36.9 L -6.3 T	169 L 225 T -59.0 L -51.3 T
Modulus at 100 percent elongation, N/mm (lbf/in), percent change	Not required	2.0 (11.4) L 1.8 (10.3) T	2.3 (13.3) L 2.0 (11.7) T +16.7 L +13.6 T	2.8 (15.8) L 2.0 (11.7) T +38.6 L +13.6 T	3.9 (22.4) L 4.3 (24.8) T +96.5 L +140.8 T
Elmendorf Tear, grams, percent change	*1500	1830 L 2290 T	2430 L +32.8 L	2900 L 2840 T +58.6 L +24.0 T	1660 L 2210 T -9.3 L -3.5 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18°C (0 °F)	10 tested 1 failure	10 tested 0 failures	10 tested 0 failures	5 tested 5 failures
Plasticizer content, percent, percent change	Not required	39.8	Not determined	35.2 -11.6	23.1 -42.0
Bonded seam strength percent of parent material	65	100	97.9	94.4	Not determined

¹BWL denotes below normal waterline.

²AWL denotes above normal waterline.

³L denotes longitudinal direction.

⁴T denotes transverse direction.

* Minimum, each direction.

Table 11b. - Physical properties test results for PVC membrane linings on Bugg Lateral, Tucumcari Project, New Mexico, installed spring 1961.

Physical Property	Specifications requirements	Sample No. B-6764 (14 yr of service, BWL)	Sample No. B-7022 (19 yr of service, BWL ¹)	Sample No. B-7023 (19 yr of service, AWL ²)
Thickness, mm (mils) percent change	0.25 (10) ±10	0.24 (9.6) -14.3	0.24 (9.6) -14.3	0.21 (8.2) -26.8
Tensile strength, N/mm (lbf/in), percent change	*3.0 (17)	4.2 (24.2) L ³ 4.6 (26.1) T ⁴ -5.5 L +14.5 T	4.6 (26.4) L 5.2 (29.8) T +3.1 L +30.7 T	5.0 (28.6) L 4.7 (26.9) T +11.7 L +18.0 T
Elongation, percent change	*225	268 L 274 T -35.0 L -40.7 T	211 L 188 T -48.9 L -59.3 T	151 L 188 T -63.3 L -59.3 T
Modulus at 100 percent elongation, N/mm (lbf/in), percent change	Not required	2.4 (13.8) L 2.4 (13.8) T +21.1 L +34.0 T	3.6 (20.5) L 4.2 (23.9) T +79.8 L +132.0 T	4.6 (26.0) L 4.2 (23.9) T +128.1 L +132.0 T
Elmendorf Tear, grams percent change	*1500	3000 L 2865 T +63.9 L +25.1 T	3000 L 2200 T +63.9 L -3.9 T	450 L 1300 T -75.4 L -43.2 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18°C (0 °F)	5 Tested 5 failures	Not determined	Not determined
Plasticizer content, percent, percent change	Not required	34.1 -14.3	27.0 -32.2	21.6 -45.7
Bonded seam strength, percent of parent material	65	Not determined	Not determined	Not determined

¹BWL denotes below normal waterline.

²AWL denotes above normal waterline.

³L denotes longitudinal direction.

⁴T denotes transverse direction.

*Minimum, each direction.

Table 11c. - Physical properties test results for PVC membrane linings on Bugg Lateral, Tucumcari Project, New Mexico, installed spring 1961.

Physical property	Specifications requirements	Sample No. 22497 (27 yr of service ,AWL ¹)
Thickness, mm (mils), percent change	0.25 (10) \pm 10	
Tensile strength, N/mm (lbf/in), percent change	*3.0 (17)	5.2 (29.6) L ² 5.6 (31.7) T ³
Elongation, percent change	*225	253 L 216 T
Modulus at 100 percent elongation, N/mm (lbf/in), percent change	Not required	3.7 (21.2) L 4.8 (27.5) T
Elmendorf Tear, grams, percent change	*1500	810 L 1540 T
Graves tear, N (lbf)	Not required	20.5 (4.6) L 22.7 (5.1) T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18 °C (0 °F)	
Bonded seam strength in sheer, N/mm (lbf/in)	2.6 (15)	5.8 (33.0)
Bonded seam strength in peel, N/mm (lbf/in)	Not required	3.5 (19.9)
plasticizer content, percent change	Not required	25.6 -35.7

¹AWL denotes above normal waterline.

²L denotes longitudinal direction.

³T denotes transverse direction.

*Minimum, each direction.

Main Canal, Kennewick Irrigation District, Washington

In December 1959, a small test section of 0.2-mm (8-mil) PVC was installed in the Main Canal from station 1325 to station 1330 (Ellsperman, 1960). The PVC was supplied in one sheet measuring 150 m (500 ft) in length by 13.2 m (44 ft) wide. The site selected by the field personnel was in a location where seepage losses had killed young apple trees in an area about 30 m (100 ft) long and 6 rows wide immediately downhill from the test section.

For the installation, the existing 2:1 slopes were flattened to 2.5:1. A 0.45-m (1.5-ft) layer of excavated earth material was removed and then replaced as the protective soil cover.

On February 12, 1991, a small sample of the PVC lining was removed from the canal for laboratory testing and evaluation (Weatherly, 1991). This 31-year-old PVC sample, shown on figures 63 and 64, is the oldest one evaluated to date by Reclamation.

Because the installation was in a curved reach of the canal, some folding and wrinkling were necessary on the inside of the curve and in the bottom, which may account for the folds shown on figure 64.

The visual examination and physical properties results are summarized in tables 12a and 12b. These results indicate that the lining is much stiffer than the original material. The plasticizer content was determined to be 19 percent. Unfortunately, the plasticizer content of the original material is unknown, so the percent loss cannot be calculated.

Tensile tests were conducted on the folds discussed above and the results are as follows:

	Folded	Unfolded
Tensile Strength, lb/in	24.2	26.1
Ultimate elongation, %	238	174

The field has reported that the plastic is still providing satisfactory seepage control.



Figure 63. - View of 0.2-mm (8-mil) PVC geomembrane installed in test section on Kennewick Main Canal, Kennewick Irrigation District, Washington, in December 1959. Photograph was taken in February 1991 after 31 years of service. Note folds in lining because of installation around a curve. Depth of soil cover is about 200 mm (8 in).



Figure 64. - Laboratory photograph of sample (23203) shown on figure 63. Tears in lining were made by shovels during removal of soil cover.

Table 12a. - Visual examination of PVC membrane lining on Main Canal, Kennewick Irrigation District, Washington, installed winter 1959.

Laboratory Sample No.	Service Life (yr)	Location in canal	sample size (m ²) (yd ²)		Remarks
23203	31	Near Sta. 1325	0.84	1.0	Sample suffered some impact damage at about 4 locations during sampling; obtained from an area where the lining had been placed over a smooth subgrade. Sample contained several folds running in the transverse direction.

Table 12b. - Physical properties test results for PVC membrane lining on Main Canal, Kennewick Irrigation District, Washington, installed winter 1959.

Physical property	Sample No. B-3098 (original)	Sample No. 23203 (31 yr of service)
Thickness, mm (mils), % change	0.20 mm (8 mil)	0.18 (7.3 mil) -8.8
Tensile strength, N/mm (lbf/in), % change	(18.6) L	4.6 (26.1) L 4.5 (25.5) T 40.3 L
Elongation, % change	290L	174L 145T -40 L
Elmendorf Tear, gm, % change	1700 L 2400 T	225 L 375 T -86.8 L -84.4 T
Graves tear, N (lbf)	Not determined	19.1 (4.3) L 20.5 (4.6) T
Plasticizer content	Not determined	19.0

L denotes longitudinal direction

T denotes transverse direction.

Fivemile Lateral, Riverton Unit, Wyoming

As part of the R&B program accomplished on the Riverton Unit from 1973 to 1985, over 41 km (26 mi) of canals and laterals were lined with PVC geomembrane. Wilkerson (1984) summarizes the lining work performed under the R&B program. Also included in the reference is a summary of lining costs.

To monitor the performance of the PVC linings, inspection and sampling of some of the canal installation on the Riverton Unit were performed under the OCCS Program. The earlier investigations were conducted on the Wyoming and Pilot Canals, and these results were reported by Morrison and Starbuck (1984).

Under the FY 86 OCCS Program, PVC samples from two locations (stations 103+96 and 309+79) on the Fivemile Lateral were evaluated. PVC lining at station 103+96, which is of 0.25-mm (10-mil) thickness, was installed in the fall of 1978 under Specifications 63-C0018 (Morrison and Starbuck, 1984). In 1978, as part of the U.S./U.S.S.R. Joint Studies on Plastic Films and Soil Stabilizers, companion material was sent to the Soviet Team for installation in special study sections on the Kakhovka Project, Ukrainian S.S.R. (Suhorukov et al., 1982).

Two 6-year-old field samples were obtained in the fall of 1984 (Long, 1984). Photographs taken during sampling are shown on figures 65 through 68.

The PVC lining at station 309+79 was installed in the fall of 1981 under Specifications 63-C0046 (Bureau of Reclamation, 1981a), and it is the first use of 0.5-mm (20-mil) PVC in Reclamation's canal lining work.

Two samples of the 0.5-mm (20-mil) PVC lining were obtained in the fall of 1985, after 4 years of service (Long, 1985). Photographs taken during sampling are shown on figures 69 and 70. Results of the visual examination of the samples from both locations are summarized in table 13.

Physical properties and chemical extraction test results for the 6-year-old 0.25-mm (10-mil) PVC field samples are summarized in table 14. Results of the physical properties tests indicate that the PVC lining has experienced some stiffening, which is evident by the increase in tensile and tear strengths and a decrease in ultimate elongation.

The stiffening of the lining was primarily caused by loss of plasticizer. Chemical extraction tests showed a plasticizer loss of 11.7 percent (by weight) for the 6-year-old sample BWL (below the waterline) and 29.7 percent for the 6-year-old sample AWL (above the waterline).

As noted in other studies (Morrison and Starbuck, 1984), the sample obtained from below the waterline showed less aging than the sample obtained from above the waterline. Results of laboratory tests also indicated that sample BWL retained good, low temperature impact properties.

Results of shear and peel tests conducted on the factory seam contained in sample BWL indicated that it is in good condition with no apparent deterioration after 6 years of service.



Figure 65. - View downstream from sample site at station 103+96. Photograph taken fall of 1984. Fivemile Lateral, Riverton Unit, Wyoming.



Figure 66. - View of exposed 0.25-mm (10-mil) PVC membrane lining (sample No. 21620) at station 103+96, canal invert. Photograph taken fall 1984. Fivemile Lateral, Riverton Unit, Wyoming.



Figure 67. - View of exposed 0.25-mm (10-mil) PVC membrane lining (sample No. 21621) at station 103+96, above waterline. Photograph taken fall 1984. Fivemile Lateral, Riverton Unit, Wyoming.



Figure 68. - View of subgrade, above waterline, at station 103+96. Photograph taken fall 1984. Fivemile Lateral, Riverton Unit, Wyoming.

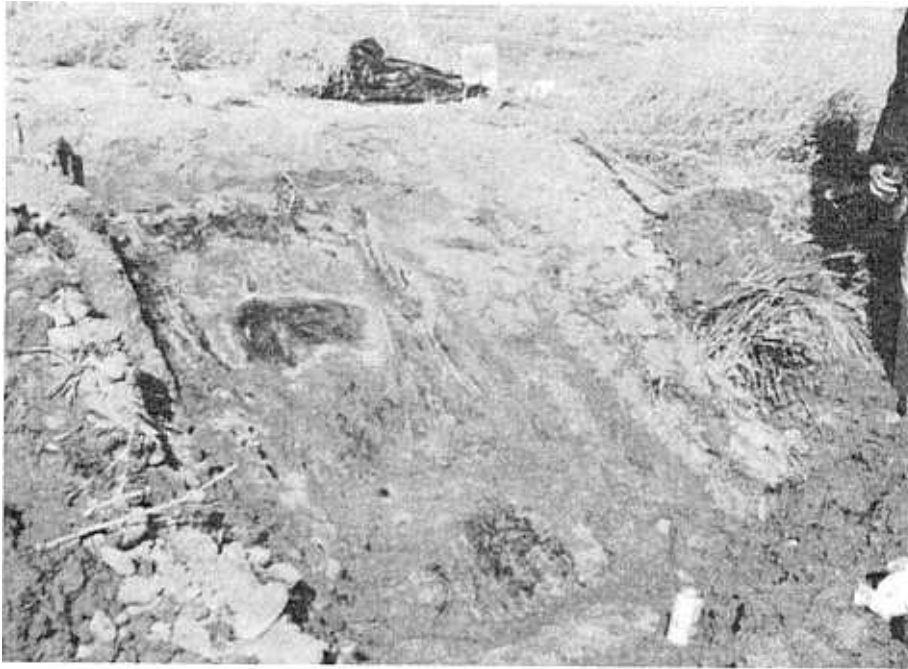


Figure 69. - View of exposed 0.50-mm (20-mil) PVC membrane lining at station 309+70. Photograph taken fall 1985. Fivemile Lateral, Riverton.

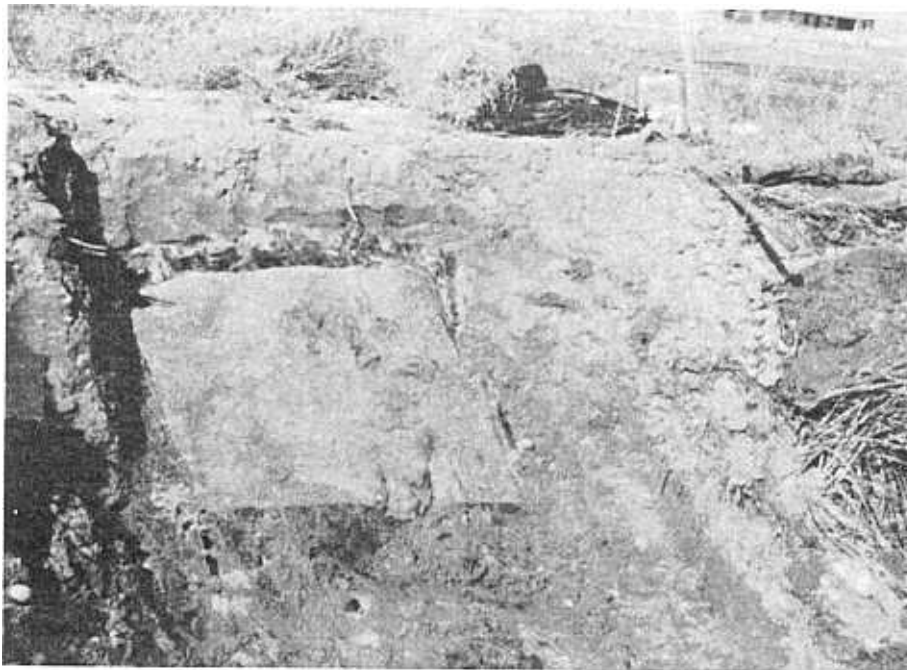


Figure 70. - View of subgrade at station 309+79. Photograph taken fall 1985. Fivemile Lateral, Riverton Unit, Wyoming.

Table 13. - Results of visual examination of PVC membrane lining samples from Fivemile Lateral, Riverton Unit, Wyoming.

Laboratory Sample No.	Service Life (yr)	Location in canal	Sample size (m ²) (yd ²)		Remarks
*21620	6	Sta. 103+96, from canal invert	0.84	1.0	Sample more flexible than sample No. 21621. Sample contained nine pinholes, five small tears, and a factory seam.
*21621	6	Sta. 103+96, from above waterline	0.71	0.85	Sample suffered some impact damage during sampling. Sample contained 1 hole, 11 tears, and 3 pinholes. Sample appeared to have been taken from an area where the subgrade was more coarse than the canal invert.
**21880	4	Sta. 309+79, from above waterline	0.79	0.94	Sample had one small tear and a fold
**21881	4	Sta. 309+79, from below waterline	0.84	1.0	Sample had seven small tears and two tears from shoveling during removal of protective cover.

* 10-mil PVC

** 20-mil PVC

Table 14. - Physical properties test results for PVC membrane linings from Fivemile Lateral, Specifications No. 63-C0018, installed fall and winter 1978-79.

Physical property	Specifications requirements	Sample No. B-6913 (original)	Sample No. 21620 (6 yr of service, BWL)	Sample No. 21621 (6 yr of service, AWL)
Thickness, (mils), % change	9	10.0	9.60	9.00
Breaking strength, (lbf/in), percent change	*20	26.1 L 24.6 T	30.0 L 36.4 T 14.9 L 7.3 T	-10.0 30.4 L 28.8 T 16.5 L 17.1 T
Elongation percent, % change	*250	220 L 267 T	194 L 240 T -11.8 L -10.1 T	166 L 223 T -24.5 L -16.5 T
Modulus at 100 percent elongation, (lbf/in), percent change	Not required	16.4 L 13.1 T	22.6 L 19.3 T 37.8 L 47.3 T	26.4 L 26.0 T 61.0 L 99.2 T
Elmendorf Tear, grams percent change	*1600	1675 L 3000 T	2300 L 4020 T 37.3 L 34.0 T	1860 L 2350 T 16.2 L -21.7 T
Graves tear, (lbf), percent change	Not required	2.9 L 3.2 T	3.9 L 3.9 T 24.1 L 21.9 T	5.0 L 5.0 T 65.5 L 56.2 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at -18 °C (0 °F)	10 tested 0 failures	5 tested 5 passed	5 tested 5 failed
Bonded seam strength in shear, (lbf/in)	16	Not tested	26.0	No sample
Bonded seam strength in peel, (lbf/in)	Not required	Not tested	12.1	No sample
Plasticizer content, percent change	Not required	33.3	29.4 -11.7	23.4 -29.7

L denotes longitudinal direction.

T denotes transverse direction.

BWL denotes below normal waterline.

AWL denotes above normal waterline.

*minimum, each direction.

Percent change is based on original values for sample B-6913

Physical properties and chemical extraction test results for the 4-year-old 0.5-mm (20-mil) PVC field samples are summarized in table 15. Test results indicate that this PVC lining is also stiffening as a result of plasticizer loss.

Table 15. - Physical properties test results for PVC membrane linings from Fivemile Lateral, Specifications No. 63-C0046, installed fall and winter 1981-82.

Physical property	Specifications requirements	Sample No. B-7102 (original)	Sample No. 21881 (4 yr of service, BWL)	Sample No. 21880 (4 yr of service, AWL)
Thickness, (mils), percent change	19	20.2	19.9 -1.5	19.5 -3.5
Breaking strength, (lbf/in), percent change	*46	52.8 L 47.6 T	57.9 L 51.5 T 9.7 L 8.2 T	58.3 L 42.8 T 10.4 L -10.1 T
Elongation percent, percent change	*300	296 L 324 T	258 L 248 T -12.8 L -23.5 T	251 L 168 T -15.2 L -48.1 T
Modulus at 100 percent elongation, (lbf/in), percent change	*18	26.6 L 22.4 T	38.2 L 34.4 T 43.6 L 53.5 T	39.2 L 35.6 T 47.4 L 58.9 T
Graves tear, lbf, percent change	*6	4.8 L 5.5 T	8.0 L 8.2 T 66.7 L 49.1 T	8.1 L 8.6 T 68.8 L 56.3 T
Impact resistance	Not more than 5 specimens out of 10 shall fail at -15 °F	10 tested 0 failures 0%	5 tested 1 failure 20%	5 tested 2 failures 40%
Bonded seam strength in shear, lbf/in	36.8	40.7	No sample	No sample
Plasticizer content, percent change	Not required	36.2	29.3 -19.1	28.5 -21.2

L denotes longitudinal direction.

T denotes transverse direction.

* Minimum, each direction.

BWL denotes below normal waterline.

AWL denotes above normal waterline.

Percent change is based on original values for sample B-7102.

Because of the increased thickness, 0.5-mm (20-mil) PVC is generally manufactured with a higher plasticizer content than the 10-mil material. Chemical extraction tests showed a plasticizer loss of 19.1 percent for the sample obtained below the waterline and a 21.1-percent loss for the sample obtained from above the waterline.

Because sample AWL also contained a fold, tensile tests were conducted on specimens from this area for comparison to those from the unfolded portion. Test results shown below indicated that the folds had no adverse effect on the tensile properties.

	Folded	Unfolded
Tensile Strength, lb/in	42.4	42.8
Ultimate elongation, %	182	168

For the most part, the PVC linings on the Riverton Unit are performing satisfactorily (Schaack and Brohl, 1986). The canal side slopes are 2:1.

To reduce the cost of the protective soil cover on the Riverton Unit, the excavated native material was used for half the cover depth, and a sand and gravel layer was used for the upper half to provide erosion protection. For the most part, this protective soil cover system has performed satisfactorily. However, a slide did occur on the Pilot Canal in 1977 between stations 610+00 and 612+00 (Jones, 1981). For a major portion of the slide, slippage occurred between the PVC and the soil underneath, which was a sandy clay with a liquid limit of 37 and a plasticity index of 19. Observations of an adjacent section of lining soon after the slide revealed ice under the lining, which may have created a slip zone. Also, during subgrade preparation, the subgrade was lightly rolled to form a smooth surface to avoid puncturing the PVC by rock particles. The requirement for rolling has since been eliminated from the specifications. Current specifications provide for dragging the subgrade with the removal of projecting particles likely to cause puncturing.

To determine the seepage control effectiveness of the PVC linings, ponding tests were conducted in 1982 (Bureau of Reclamation, 1983) on a reach of the Fivemile Lateral lined with 10-mil PVC, and in 1983 (Bureau of Reclamation, 1984a) on a reach of the same lateral lined with 20-mil PVC. The test results are summarized below.

Location (stations)	Lining Thickness mm (mils)	Seepage Rate	
		m ³ /m ² •day	ft ³ /ft ² •day
200+00 to 207+00	0.25 (10)	10	0.0060
309+00 to 314+42	0.50 (20)	20	0.00435

For comparative purposes, ponding tests were conducted on several unlined canals and laterals (Wilkerson, 1984) in 1973/1974 at the beginning of the R&B Program and the seepage losses ranged from 0.061 m³/m²•day (0.2 ft³/ft²•day) to 0.5 m³/m²•day (1.54 ft³/ft²•day), indicating that seepage has been reduced by at least 90 percent.

South Canal, Belle Fourche Unit, South Dakota

Test sections of three recently developed geomembranes were installed on the South Canal between 1987 and 1992 to evaluate their effectiveness for seepage control in irrigation canals. The materials are VLDPE (very low density polyethylene), polyolefin geomembrane/geotextile composite lining (GT/LDPE/GT), and unreinforced PP (polypropylene) geomembrane. These materials are being evaluated as possible alternatives to PVC.

VLDPE was developed primarily for use as a capping material in the final closure of landfills (Cadwallader, 1990). VLDPE is more flexible than HDPE.

To improve the slope stability of soil covers, industry is now developing geomembranes with frictional surfaces. One such material, a polyolefin composite lining (GT/LDPE/GT), was selected for field testing to evaluate its effectiveness for improving soil cover stability on side slopes. This material is a composite consisting of a 118-g/m² (3.5-oz/yd²) needle-punched non-woven polypropylene geotextile laminated to both sides of a 0.05- to 0.08-mm (2- to 3-mil) thick LDPE (low density polyethylene) liner. The composite can also be manufactured with the geotextile on one side only.

A PP resin was recently developed for use in manufacturing geomembranes. PP is more flexible than HDPE. PP has a lower coefficient of thermal expansion than HDPE and VLDPE, which makes it easier to install.

The following paragraphs describe the three test sections.

VLDPE test section. - In April 1987, a 150-m (500-ft) test section of a 0.75-mm (30-mil) VLDPE was installed in the South Canal from station 523+00 to station 528+00. This reach was selected because the site met the criteria for cross-section width, which were 15 m (50 ft) or less with 2.5:1 side slopes, had no access, and was protected from drainage water entering the canal on the uphill side. Also, lands located below this reach experienced seepage problems.

The manufacturer of the VLDPE lining donated the material and provided a technical representative to make the field seams, and the local irrigation district furnished the equipment and personnel to install the geomembrane. Three rolls of lining, each 7.5 by 120 m (25 by 400 ft) in size, were furnished by the manufacturer (Bureau of Reclamation, 1987a). Installation of the geomembrane is shown on figures 71 to 76. Two different protective soil covers are being evaluated. One-half of the test reach was covered with 300 mm (12 in) of pit-run gravel, and the other half with 150 mm (6 in) of pit-run gravel placed over 150 mm (6 in) of excavated material.

As part of the study, test coupons, each measuring about 0.3 by 1.5 m (1 by 5 ft), were installed on the side slope of the canal as shown on figure 77 to allow periodic retrieval for testing and evaluation. Test results for coupon samples retrieved after 1, 2, and 5 years of service are summarized in table 16. Results of these tests indicate that no apparent deterioration of the lining occurred.

The canal was inspected in May 1988 after 1 year of service, as shown on figures 78 and 79, and again in October 1990, and no evidence of any problems with soil cover stability were found.



Figure 71. - View of local irrigation district personnel unrolling VLDPE in test section at station 528+00, South Canal, Belle Fourche Unit, South Dakota. The 0.75-mm (30-mil) geomembrane was furnished in rolls 7.5 by 120 m (25 by 400 ft) in size.



Figure 72. - View of labor crew unrolling second roll of VLDPE.



Figure 73. - View of labor crew installing VLDPE on left slope.



Figure 74. - View of labor crew preparing to heat weld centerline seam. The factory representative supervised the installation and operated the fusion welding machine to make the field seams.



Figure 75. - View of factory representative making field seam along centerline, progressing upstream from station 529+00. Material was overlapped about 100 mm (4 in) although 50 mm (2 in) would work. Temperature of the heat welder is about 300 °C.



Figure 76. - View of completed test section before placement of protective soil cover. The installation of the geomembrane in the 150-m (500-ft) long test section was completed in one day. Photograph taken April 15, 1987.

Table 16. - Physical properties test results for very low density polyethylene membrane lining on South Canal, Belle Fourche Project, South Dakota.

Physical Property	Original	1 yr of service		2 yr of service		5 yr of service	
		BWL	AWL	BWL	AWL	BWL	AWL
Thickness, mm (mils)	0.86 (33.8)	0.83 (32.7)	0.85 (33.3)	0.89 (35.2)	0.88 (34.5)	0.83 (32.8)	0.81 (32.0)
Breaking force N (lb _f)	490+ (110+) L 445+ (100+) T	445+ (100+) L 445+ (100+) T	445+ (100+) L 445+ (100+) T	490+ (110+) L 445+ (100+) T	490+ (110+) L 490+ (111+) T	490+ (110+) L 445+ (100+) T	490+ (110+) L 445+ (100+) T
Ultimate Elongation, percent	800+L	800+L	800+L	800+L	820+L	820+L	830+L
Percent of Specimens not breaking at machine elongation limit	830+T 80 L 80 T	830+T 80 L 80 T	775+T 60 L 40 T	850+T 60 L 60 T	850+T 60 L 0 T	830+T 80 L 60 T	850+T 100 L 80 T
Graves tear resistance N (lb _f)	70.3 (15.8) L 74.8 (16.8) T	65.3 (14.7) L 65.0 (14.6) T	63.6 (14.3) L 65.0 (14.5) T	85.4 (19.2) L 83.6 (18.8) T	88.6 (19.9) L 79.1 (17.8) T	70.2 (15.8) L 71.6 (16.1) T	Not determined Not determined 62.2 (14.0) T

+ Indicates some specimens did not break at the limit of the testing machine movement.

BWL denotes below waterline.

AWL denotes above waterline.

L denotes longitudinal direction.

T denotes transverse direction.

Note: The tensile test was conducted in accordance with ASTM D-638; Type IV die, gage length of 5 mm, and rate of grip separation of 5 mm. The tear test was conducted in accordance with ASTM D-1004. Reported values are average of 5 specimens cut from the coupon in the direction indicated.

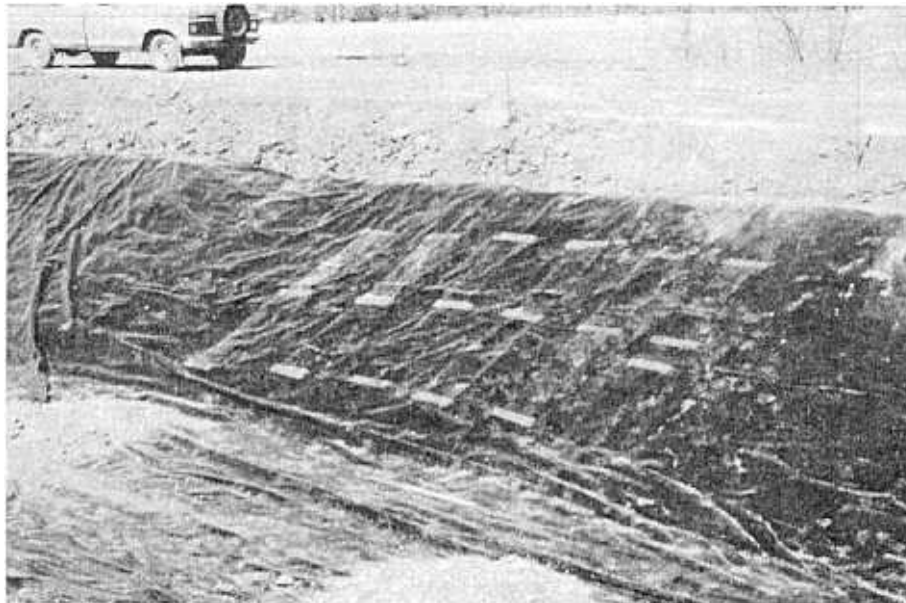


Figure 77. - View of test coupons taped to lining on left slope, just upstream from station 528+00. The coupon samples measuring about 0.3 by 1.5 m (1 by 5 ft) were installed both above and below waterline and will be removed periodically for testing and evaluation.



Figure 78. - Photograph taken May 1988 showing test section of VLDPE, South Canal, Belle Fourche Unit, South Dakota, after 1 year of service. View looking downstream. Steel post in center of photograph notes the change in cover material. Downstream, the cover material was 0.3 m (12 in) of pit-run gravel, and upstream, cover material was 150 mm (6 in) of excavated earth material and 150 mm (6 in) of pit-run gravel.



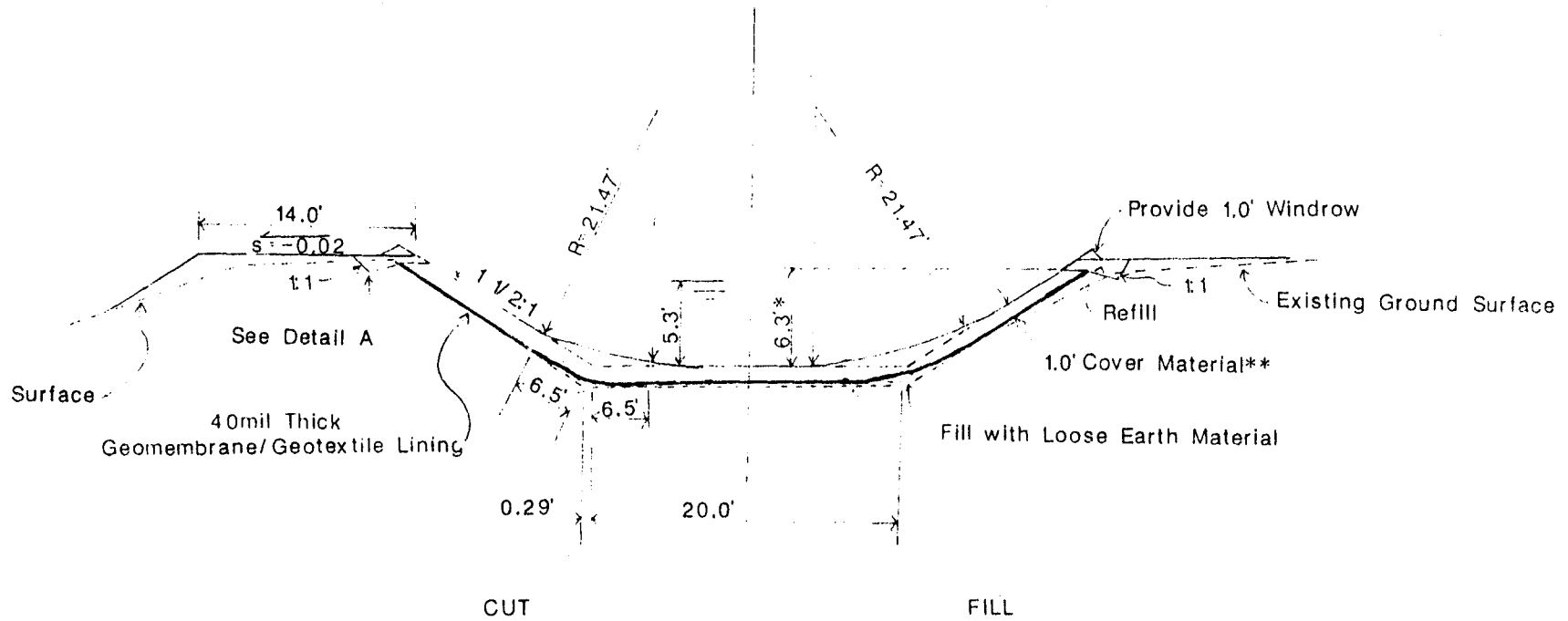
Figure 79. - View upstream looking at VLDPE test section where 150 mm (6 in) of earth and 150 mm (6 in) of gravel was used as the cover material. No evidence has been found of any problems with soil cover stability in the test section after 1 year of service.

Polyolefin composite lining test section. - A 150-m (500-ft) test section of GT/LDPE/GT composite lining was installed in April 1990 in the South Canal from station 299+00 to station 304+00. A typical section of the test reach is shown on figure 80. The lining material was furnished at cost by the manufacturer, and the local irrigation district provided equipment and labor to install the lining. A representative of the manufacturer was present during the installation to provide technical assistance.

The composite material was furnished in rolls 3.6 m (12 ft) wide by 90 m (300 ft) in length. To reduce the amount of field seaming, the roll goods were preseamed to form sheets wide enough (about 16.5 m [55 ft]) to cover the width of the canal and about 30 m (100 ft) in length. This work was accomplished inside the irrigation district's warehouse. The roll goods were overlapped about 150 mm (6 in) at the seams and sealed with a hot-applied rubberized asphalt adhesive. The adhesive was applied at a temperature of about 166 °C (330 °F) in a bead about 38 mm (1.5 in) wide in the overlapped area. The seam was then rolled with a rubber tire (similar to a wheelbarrow tire) to work the adhesive into the fabric of both layers to form a watertight seam. Installation of the composite lining is shown on figures 81 to 85.

The canal side slopes are 1.5:1. About 300 mm (12 in) of a pit-run gravel was placed on the geomembrane lining to act as a protective layer. Gradation of the material is shown in table 17. The completed test section is shown on figure 86.

To monitor the performance of the lining, coupon samples were placed in the canal as shown on figure 87. These samples will be retrieved periodically for testing and evaluation.



TYPICAL SECTION

Figure 80. - Cross sectional view of GT/LDPE/GT composite lining test section; South Canal, Belle Fourche Unit, SD.



Figure 81. - View looking downstream at test section for polyolefin composite lining in South Canal, Belle Fourche Unit, South Dakota. Workmen are making final cleanup of rock, soil clod, and rocks.



Figure 82. - View of transverse seaming of polyolefin composite lining. Hot, rubberized asphalt adhesive is applied at seam overlap.



Figure 83. - View of seaming operation on side slope.

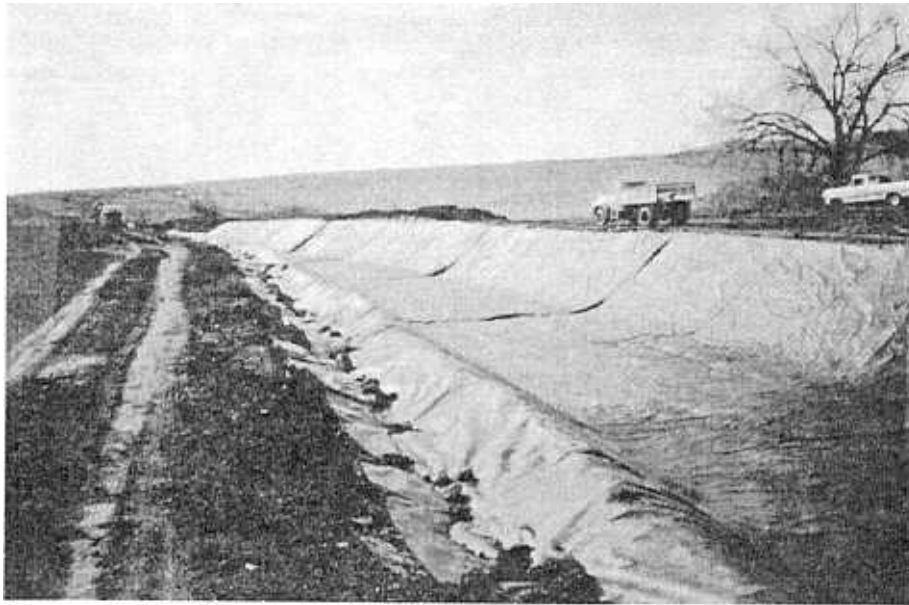


Figure 84. - View of installed polyolefin lining showing four transverse field seams. View is looking downstream before filling anchor trenches.

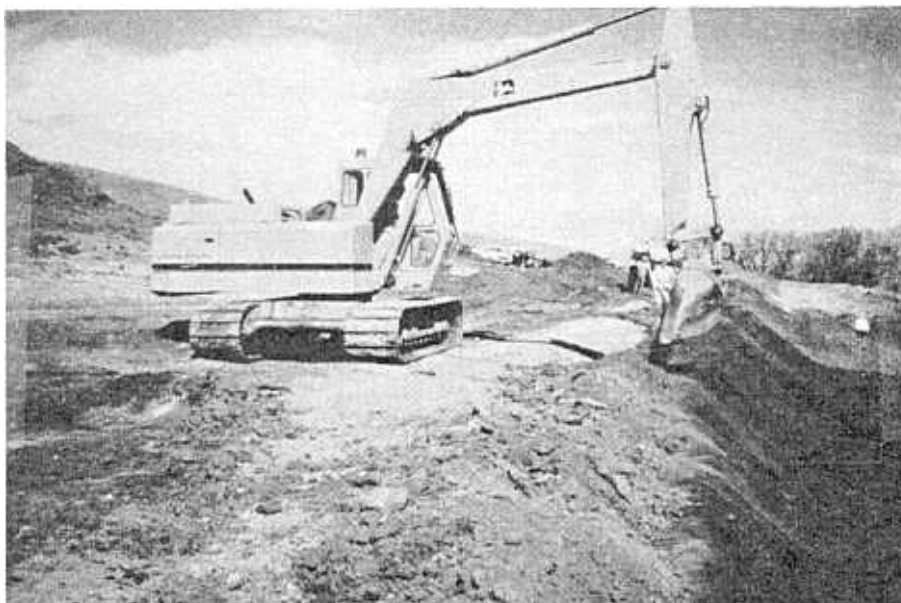


Figure 85. - View looking upstream showing the filling of the side anchor trenches.

Table 17. - Gradation of soil cover used on polyolefin composite lining, South Canal, Belle Fourche Unit, South Dakota.

Screen size	Percent passing screen (by weight)
1-½ inches	100
¾ inch	97
¾ inch	92
No. 4	90
No. 8	88
No. 16	86
No. 30	84
No. 50	80
No. 100	76
No. 200	72
Unified soil classification	CL
Liquid limit (%)	36.2
Plasticity index (%)	20.1



Figure 86. - View looking upstream of completed test section of polyolefin composite lining.



Figure 87. - View of test coupons installed in canal to monitor performance of the polyolefin composite lining.

The canal was inspected in September 1993, at 3½ years old, after the irrigation season, and the soil cover appeared to have remained stable on the 1.5:1 slopes as shown on figures 88 and 89. Also, some previously wetted areas adjacent to the lined section are showing signs of less seepage.

Laboratory tests were conducted on samples of the composite lining that was installed. Test results are summarized in table 18. Tests were also conducted on samples of field seams subjected to laboratory water immersion. Test results for these samples after 3, 12, and 52 weeks of immersion are summarized in table 19.



Figure 88. - View of test section of polyolefin composite lining taken September 1990 after irrigation season. The soil cover has remained stable on the 1.5:1 side slopes.



Figure 89. - Note standing water in test section. This area was left in "rough condition" after construction and not graded. The remaining test section was to grade and sloped properly to drain.

Table 18. - Results of laboratory tests for polyolefin composite lining installed on South Canal, Belle Fourche Unit, South Dakota.

Physical property	ASTM test method	Test results
Tensile strength, N/mm (lbf/in)	D 882	6.4 (36.4) L 6.0 (34.3) T
Elongation, percent	D 882	30 L 62 T
Breaking strength, N (lbf)	D 751, Grab, Method A	740 (166) L 580 (131) T
Graves, tear, N (lbf)	D 1004	34.3 (7.7) L 28.5 (6.4) T
Tongue tear, N (lbf)	D 751 as modified in appendix A of NSF Standard No. 54	210 (47.1) L 100 (40.5) T
Hydrostatic resistance kPa (lb/in ²)	D 751, Method A, procedure 1	2090 (303)

L denotes longitudinal direction
T denotes transverse direction

Table 19. - Results of laboratory tests conducted on field seam samples of polyolefin composite lining installed on South Canal, Belle Fourche Unit, South Dakota.

Seam Property	Water Immersion Period				
	(0) original	6 weeks	3 months	6 months	1 year
Shear (N/mm) (lbf/in)	2.4 13.9	4.0 22.6	3.7 20.9	3.1 17.8	3.1 17.8
Peel (N/mm) (lbf/in)	0.6 3.3	0.7 3.9	0.5 3.1	0.8 4.7	0.6 3.3

Polypropylene lining test section. - A 150-m (500-ft) test section of 0.75-mm (30-mil) PP was installed in the South Canal from station 294+29.25 to station 299+29.25 in April 1992. This reach is immediately adjacent to the composite lining test section; however, the slopes were overexcavated to 2.5:1.

The resin and geomembrane manufacturers donated the geomembrane. Both companies provided technical representatives to assist in the installation and make the field seams; again, the local irrigation district furnished the equipment and personnel to install the geomembrane and cover material. This installation is shown on figures 90 through 93.

The geomembrane rolls were factory assembled so that the only field seam necessary was located between adjacent panels. Geomembrane panels were folded and rolled and delivered to the job site. The factory seams were welded with a dual-track hot-wedge welding machine. The same hot-wedge machine was to be used to perform field seaming; however, the equipment did not work well in the field. The soft subgrade and the very warm day made the geomembrane very soft and pliable. This condition caused the material to bunch up in the equipment. Therefore, the field seams were made with a hot air gun and a hand roller as shown on figure 94. The PP liner was shingled and hot air tacked to a cleaned-off section of the composite lining test section.

To monitor the material, eleven sets of test coupons were installed on the sideslope of the test section. Each coupon contained a factory and field seam, and each set consisted of one coupon installed at the bottom of the slope and one coupon at the normal waterline. Project personnel marked the location of the test coupons, which will be retrieved at various time intervals for laboratory testing.

In February 1993, field personnel reported that the liner performed well throughout the first irrigation season. Results of physical properties of the original material and samples retrieved after 1.5 and 3 years in service are summarized in table 20. The Project Manager's Office in Newell, South Dakota, and the Technical Service Center, will continue to monitor these test sections on the South Canal.



Figure 90. - View of canal section prepared with side slopes 2.5:1 for placement of PP lining.



Figure 91. - View of adjacent composite test section to which the PP will be joined by hot air welding.



Figure 92. - View of PP rolls as delivered to the job site.



Figure 93. - View of PP panel placement.



Figure 94. - Hot air welding of transverse seams in the PP test section at Belle Fourche, South Dakota.

Table 20. - Physical properties test results for polypropylene after 3.0 years of service on South Canal, Belle Fourche Project, South Dakota.

Physical Property	Test Method	Original	1.5 yr Exposure		3 yr Exposure	
			AWL	BWL	AWL	BWL
Thickness (mils)	ASTM D751 (as modified in NSF* 54)	30.8	28.3	29.3	28.3	28.4
Seam Shear Strength (lbf)	ASTM D4437 (as modified in NSF 54)	N/A	49.2 Factory 30.5 Field	48.0 Factory 29.1 Field	48.6 Factory 40.7 Field	47.5 Factory 38.5 Field
Seam Peel Strength (lbf)	ASTM D4437 (as modified in NSF 54)	N/A	35.1 Factory 12.3 Field	35.3 Factory 19.1 Field	33.4 Factory 17.4 Field	34.1 Factory 14.8 Field
Graves Tear Resistance (lbf)	ASTM D1004	14.4L 12.9T	14.2 N/S (L) 14.6 E/W (T)	15.1 N/S (L) 15.5 E/W (T)	14.4 N/S (L) 14.7 E/W (T)	14.8 N/S (L) 14.4 E/W (T)
Tensile Strength at Break (lbf/in)	ASTM D638 (as modified in NSF 54)	95.1L 82.5T	84.3 N/S (L) 87.5 E/W (T)	83.8 N/S (L) 93.4 E/W (T)	86.3 N/S (L) 85.7 E/W (T)	88.2 N/S (L) 94.3 E/W (T)
Elongation at Break (percent)	ASTM D638 (as modified in Annex A	1157L 1146T	1173 N/S (L) 1173 E/W (T)	1206 N/S (L) 1167 E/W (T)	1253 N/S (L) 1063 E/W (T)	1315 N/W (L) 1197 E/W (T)

*NSF - National Sanitation Foundation

New Rockford Canal, Garrison Diversion Unit, North Dakota

Between 1985 and 1991, over 44 km (28 mi) of the New Rockford Canal were constructed under two contracts, DC-7647 and DC-7747 (Bureau of Reclamation, 1985a; 1988a). About 27 km (17 mi) of the canal were lined with 0.5-mm (20-mil) PVC, and the remainder with compacted earth. Some sloughing of the protective soil cover on the PVC lining has occurred, and the following paragraphs provide background information on the stability problem (Bureau of Reclamation, 1990a). A total of 989,000 m² (1,183,000 yd²) of PVC was installed.

Reach 1A, Specifications No. DC-7647. - The original design called for installing PVC lining with 150 mm (6 in) of sand and gravel cover over 380 mm (15 in) of earth cover on 2:1 slopes, from station 126+00 to station 433+91.13.

The contractor began construction in August 1985 and started PVC lining placement on September 2, 1986. By November 2, 1986, they had placed PVC lining with 380 mm (15 in) of earth cover between stations 126+00 and 191+70. PVC lining operations stopped for the season at that point.

When construction operations resumed in 1987, the contractor placed 150 mm (6 in) of sand and gravel cover on top of the earth cover which had been placed in 1986. This operation took place during May and June of 1987.

Also, in May and June 1987, the contractor placed PVC lining with both cover materials between station 368+23 and station 432+48. By July 21, 1987, the contractor had placed PVC lining with both cover materials between station 191+70 and station 224+80.

On July 21, 1987, about 56 mm (2.2 in) of rain fell in the area, accompanied by strong easterly winds. The storm damaged the PVC lining cover material considerably. Numerous, almost continuous slides occurred on the left side slope from stations 381+80 to 432+48. This canal reach lies in a SW-NE direction and therefore was directly impacted by the easterly winds. Slides occurred on about one-third of the length on the right side slope, which lay on the leeward side of the strong winds in this area.

Smaller slides also occurred on the left side between stations 154+00 and 224+50.

Laboratory tests of the earth portion of the cover material from both the stable slope areas and the unstable slope (slide) areas were run. The results are summarized in table 21. As-built lining cover thicknesses and gradations are summarized in table 22. No obvious conclusions can be made from this soil testing.

After consulting with the Technical Service Center designers, a decision was made to pull the cover material back up the slopes and regrade it. No attempt was made to separate the two types of material when they were placed back on the PVC lining.

Table 21. - Results of laboratory tests on PVC soil cover material, New Rockford Canal, Reach 1A, Garrison Diversion Unit, North Dakota.

Stable slope areas						
Station	Soil Classif.	Percent fines		Percent sand	LL(%)	PI(%)
		< 2 μ	> 2 μ			
135+00 Lt.	SM	13	23	64	-	-
185+00 Lt.	SM	10	23	67	-	-
195+00 Lt.	SP-SM	7	3	90	-	-
198+00 Lt.	SC-SM	8	35	57	20	5
386+00 Lt.	CL-ML	24	33	43	22	7

Unstable slope areas						
Station	Soil Classif.	Percent Fines		Percent sand	LL(%)	PI(%)
		< 2 μ	> 2 μ			
154+00 Lt.	SM	11	21	68	-	-
186+00 Lt.	SC-SM	17	28	55	18	4
390+00 Lt.	SC-SM	19	28	53	19	5
402+50 Lt.	SM	13	30	57	-	-
407+00 Lt.	SM	10	28	62	-	-
414+00 Lt.	SM	11	30	59	-	-
425+00 Lt.	SM	10	36	54	-	-
431+00 Lt.	SM	7	30	63	-	-

The contractor then resumed placing PVC lining with cover material as originally specified. On July 30, 1987, the contractor was directed to change the thickness of the sand and gravel cover to 300 mm (12 in) and earth cover to 530 mm (21 in). This change began at station 230+61 and continued to station 269+90.

On August 11, 1987, the contractor was directed to change the gradation of the sand and gravel cover material. This change began at station 269+90. By September 20, 1987, all cover material for the contract was placed. Table 22 summarizes the as-built cover thicknesses and gradation of sand and gravel cover materials.

Since completion of the contract on November 23, 1987, additional damage to the cover material has occurred. All damage was caused by rainfall and melting snow. On March 9, 1988, a slide was observed near station 344+50 left. On March 10, 1988, seven or eight slides were observed on the left side between stations 300+50 and 363+75. As of March 28, 1988, slides or cracks had developed in 19 locations, totaling more than 300 m (1,000 ft) in length.

Table 22. - As-built lining cover thicknesses and gradations for New Rockford Canal, Reach 1A, Garrison Diversion Unit, North Dakota.

From Station	To Station	Thickness		Gravel cover gradation*	Comments
		Bottom	Side Slopes		
126+00	191+70	6 in. gravel 15 in. earth	6 in. gravel 15 in. earth.	1	
191+70	230+61	15 in. earth	15 in. earth	-	
230+61	269+90	21 in. earth	12 in. gravel	1	
269+90	368+23	21 in. earth	12 in. gravel	2	
368+23	381+80	3 in. gravel 15 in. earth	6 in. gravel 15 in. earth	1	Gravel on right side only
381+80	432+48	- 15 in. earth	6 in. gravel 15 in. earth	1	Cover on slopes was mixed when replaced
432+48	432+91	21 in. earth	12 in. gravel	2	

Gravel Cover Gradations *

Gradation 1		Gradation 2	
Screen size	Percent passing screen (by weight)	Screen size	Percent passing screen (by weight)
8 inches	100	6 inches	100
3 inches	80 - 100	3 inches	70 - 95
1 - ½ inches	50 - 90	2 inches	55 - 75
¾ inch	20 - 80	1 - ¼ inches	30 - 60
½ inch	10 - 65	¾ inch	15 - 45
No. 4	5 - 50	¾ inch	10 - 25
No. 8	0 - 40	No. 4	0 - 15
No. 16	0 - 30	No. 40	0 - 5
No. 30	0 - 25		
No. 50	0 - 20		
No. 100	0 - 15		
No. 200	0 - 10		

On April 11, 1989, a survey of additional damage to the PVC lining cover disclosed the existence of nine major slide areas with a total approximate length of 400 m (1,300 ft). A complete survey of cover lining conditions, completed on October 26, 1989, showed damage of varying types at 47 locations. The results of this survey are summarized in table 23. Four modes of failure were observed:

- Mode 1. Small erosion "rills" or channels running straight down the slopes without exposure of PVC lining.
- Mode 2. Larger erosion "rills" where the channels are deep enough to expose the PVC lining and form a "delta" at the toe of the slope.
- Mode 3. "Slump" areas where the cover material slid down the PVC lining without exposing the lining.
- Mode 4. Slide areas where a "slump" progressed to the point of exposing the PVC lining.

Conclusions

The cover material was placed on the PVC lining in an unconsolidated state, as is the normal practice. Normally, during the first filling of the canal after construction, the cover material tends to consolidate, sometimes even "slumping" in some areas. This consolidation helps to resist erosion thereafter. Because the completed reaches of the New Rockford Canal have never been filled with water, the cover material remains in an unconsolidated state.

The cover material absorbed enough runoff water to saturate the material, making it unstable. This instability is probably the result of two events. First, the weight of the cover material increases to the point of overcoming the friction force which holds the material on the side slope. Second, the presence of water tends to decrease the friction factor between the material and the lining by "lubricating" the cover material.

Irrigation canals are usually designated to transport water for about 6 months of the year, which limits the exposure to surface runoff to a 6-month period when the canal is normally empty. During this empty period, a canal prism in North Dakota would normally be frozen for a period of 3 months and therefore, resistant to erosion. This timing would leave a "window" of about 3 months when the canal would be vulnerable to surface runoff erosion. Such erosion would normally be minimal.

New Rockford Canal, however, is not a normal canal, in that the constructed reaches of the canal have yet to be used to transport water. This lack of use leaves the canal exposed to the elements all year instead of during a brief 3-month window.

Contributing factors to cover material failure were the type, gradation, and thickness of cover material, side slope, and the direction that the side slope faced.

Reach 2, Specifications No. DC-7747. - In an attempt to create a more stable condition on Reach 2, the side slopes were changed to 2.5:1 during the bidding stage of the contract. Also, the gradation for the gravel cover material was the same as the revised gradation used on Reach 1A.

Table 23. - Results of survey on locations of damaged lining covers as of October 26, 1989, New Rockford Canal, Reach 1A, Garrison Diversion Unit, North

From	Station To	Photo Station	Exposed lining	Lining cover type*	Remarks
194+03 Lt.	194+25 Lt.	194+14 Rt.	Yes	A	Lining covered by O&M
194+50 Lt.	194+70 Lt.	194+61 Rt.	Yes	A	Lining covered by O&M
206+43 Lt.	206+72 Rt.	206+60 Lt.	Yes	A	
207+49 Rt.	207+57 Rt.	207+52 Lt.	Yes	A	
239+23 Rt.	239+25 Rt.	239+25 Lt.	Yes	B	Wash from O*M road
277+81 Rt.	278+33 Rt.	278+04 Lt.	No	C**	Ramp location during const.
300+75 Rt.	301+75 Rt.	301+25 Lt.	No	C	
302+62 Rt.	303+12 Rt.	302+70 Lt.	No	C	
307+98 Lt.	308+22 Lt.	308+12 Rt.	-	C	Lining covered by O&M
308+49 Lt.	308+65 Lt.	308+57 Rt.	-	C	Lining covered by O&M
311+90 Lt.	312+12 Lt.	312+04 Rt.	No	C	
312+32 Lt.	314+15 Lt.	313+78 Rt.	No	C	
317+08 Lt.	317+61 Lt.	317+32 Rt.	No	C	
317+76 Lt.	318+13 Lt.	317+90 Rt.	No	C	
321+02 Lt.	321+59 Lt.	321+30 Rt.	No	C	
327+08 Lt.	327+81 Lt.	327+45 Rt.	No	C	
328+33 Lt.	328+63 Lt.	328+45 Rt.	No	C	
330+81 Lt.	332+18 Lt.	331+65 Rt.	No	C	
335+51 Lt.	336+28 Lt.	336+00 Rt.	No	C	
337+63 Lt.	338+22 Lt.	338+00 Rt.	No	C	
341+63 Lt.	341+98 Lt.	341+90 Rt.	No	C	
344+50 Lt.	344+76 Lt.	344+66 Rt.	No	C	
345+22 Lt.	345+58 Lt.	345+40 Rt.	No	C	
345+99 Lt.	346+75 Lt.	346+32 Rt.	No	C	
348+18 Rt.	2 feet above toe		Yes	C	1- x 2-foot area exposed < 12-inch gravel cover in area
349+35 Rt.	4 feet above toe		Yes	C	4- x 4-foot area exposed < 12-inch gravel cover in area
350+93 Lt.	351+11 Lt.	351+02 Rt.	No	C	
370+30 Lt.	370+77 Lt.	370+55 Rt.	-	D	Lining covered by O&M
371+33 Lt.	371+48 Lt.	371+40 Rt.	-	D	Lining covered by O&M
371+60 Lt.	372+02 Lt.	371+80 Rt.	-	D	Lining covered by O&M
372+17 Lt.	373+05 Lt.	372+55 Rt.	-	D	Lining covered by O&M
375+03 Lt.	375+17 Lt.	375+10 Rt.	-	D	Lining covered by O&M
375+41 Lt.	375+82 Lt.	375+70 Rt.	Yes	D	
376+02 Lt.	377+25 Lt.	376+50 Rt.	Yes	D	
377+31 Lt.	378+22 Lt.	377+95 Rt.	No	D	
378+47 Lt.	378+81 Lt.	378+65 Rt.	No	D	
379+89 Lt.	380+46 Lt.	380+10 Rt.	Yes	D	
380+56 Lt.	380+75 Lt.	380+65 Rt.	No	D	
389+90 Rt.		389+90 Lt.	Yes	-	Riprap at pumping plant outlet
409+60 Lt.	409+81 Lt.	409+70 Rt.	No	E	
413+25 Lt.	414+17 Lt.	413+56 Rt.	Yes	E	
415+96 Lt.	416+34 Lt.	416+15 Rt.	No	E	
416+51 Lt.	417+06 Lt.	416+85 Rt.	No	E	
417+21 Lt.	417+64 Lt.	417+35 Rt.	No	E	
417+80 Lt.	418+26 Lt.	418+00 Rt.	Yes	E	
418+63 Lt.	418+92 Lt.	418+78 Rt.	No	E	
419+72 Lt.	420+58 Lt.	420+15 Rt.	Yes	E	

*Lining cover type - prism slope.

A. 15 inches earth.

C. 12 inches gravel - Gradation 2.

B. 12 inches gravel - Gradation 1.

D. 15 inches earth, 6 inches gravel - Gradation 1.

E. 15 inches earth, 6 inches gravel - Gradation 1, mixed

**Earth with 12 inches gravel - Gradation 2.

A portion of Reach 2 was constructed in areas of high ground water. To aid in dewatering during construction and operation of the canal, about 10 km (6.3 mi) of buried pipe drains were installed in these areas.

The PVC lining and buried pipe drains are designed to function together as one system. The PVC lining barrier provides side slope stability by preventing sloughing caused by ground water entrance, and it also stops water loss from the canal. The drains relieve hydrostatic water pressure under the PVC lining by lowering the ground water table in the immediate vicinity. Relieving this pressure is critical when the canal is empty. Drains without lining will not remove enough ground water to prevent the side slopes from becoming saturated and sloughing because of their limited capacity. Both lining and drains are required to make the system function correctly.

The contract for Reach 2 was awarded July 22, 1988, but budget problems delayed PVC installation until the 1990 construction season. During this construction season, the contractor placed 385,000 m² (460,000 yd²) of PVC lining from station 1625+25.90 to about station 1959+90, leaving a gap immediately upstream and downstream from the check at station 1825+00. This work amounted to about 59 percent of the total of lining to be placed.

The contractor placed the remainder of the PVC lining during the 1991 construction season. The total amount of lining placed under the contract was 654,600 m² (783,000 yd²).

Two severe local rainstorms occurred during the 1991 construction season on June 22 and September 14 and 15, 1991. Both storms caused extensive damage to the cover material; the September storm was the more severe storm. The damage varied from longitudinal cracks to movement of the cover materials onto the prism bottom. In a few instances, the PVC lining was exposed but not displaced or damaged.

The contractor repaired the sloughs (at Government expense) by dragging cover materials back up the slope with their backhoe and regrading the slopes to the design dimensions.

The modification for the June storm cost about \$5,100; the modification for the September storm cost around \$32,000. The September sloughs could be divided into the following categories:

- A. - Major slough with movement of cover material onto the prism bottom
- B. - Moderate slough on the slopes only, bottom intact
- C. - Minor slough or crack opening

About 61 percent of the sloughs were considered type A, 21 percent type B, and 18 percent type C (table 24). Examples of these sloughs are shown on figures 95 to 97.

Because the canal will not be put into operation for some time, a program to monitor the PVC-lined sections of both reaches 1A and 2 has been undertaken by the Bismarck, North Dakota, Office. This program involves taking photographs periodically to see what changes have occurred. The data will be evaluated to determine if a correlation exists between the severity and frequency of slides and such factors as type, gradation and thickness of cover material, canal side slope, and the direction that the side slope faces.

Table 24. - Tabulation of PVC lining sloughs as of September 15, 1991, New Rockford Canal, Reach 2, Garrison Diversion Unit, North Dakota.

Station to station		Right side of Canal Length (ft)	Type
1872+57	- 1872+95	38	A
1874+56	- 1874+88	32	A
1878+37	- 1879+25	88	A
1950+00	- 1950+57	57	B
1959+00	- 1960+76	176	A
1964+00	- 1965+43	143	A
1970+00	- 1971+97	197	A
1972+00	- 1972+55	55	A
1974+12	- 1975+00	88	A
1985+56	- 1986+14	58	A
1988+33	- 1992+35	402	A
1994+66	- 1995+20	54	B
1997+97	- 1998+27	30	A
2001+99	- 2003+18	119	B
2003+43	- 2004+49	106	C
2005+11	- 2005+80	69	C
2008+06	- 2009+11	105	A
2010+50	- 2010+89	39	B
2013+56	- 2015+04	148	B
2015+85	- 2018+55	270	B
2028+44	- 2030+96	252	B
2037+80	- 2039+10	130	A
2040+00	- 2041+85	185	A
2068+00	- 2071+50	350	A
2075+00	- 2077+20	220	A
2114+30	- 2115+45	115	B
2202+00	- 2202+80	80	B
		Left side of canal	
1981+00	- 1982+50	150	A
1983+50	- 1984+50	100	A
1989+00	- 1990+00	100	A
1993+00	- 1995+80	280	A
1998+00	- 1999+50	150	C
2004+00	- 2008+40	440	A
2016+50	- 2017+00	50	B
2028+00	- 2031+85	385	C
2036+00	- 2039+00	300	C

Lining cover type - prism slope.

- A. 15 inches earth.
- B. 12 inches gravel - Gradation 1.
- C. 12 inches gravel - Gradation 1, mixed.

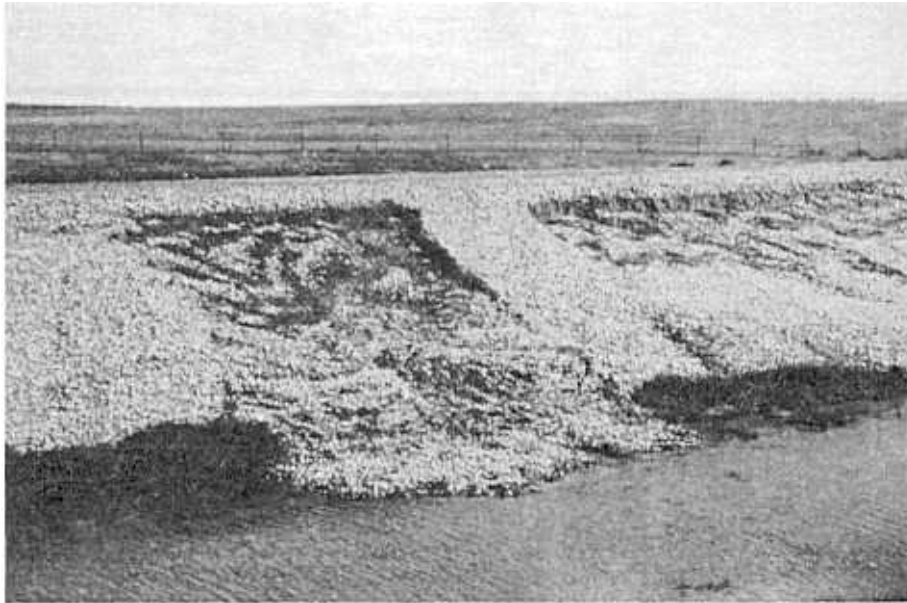


Figure 95. - View of protective soil cover slippage on New Rockford Canal, Reach 2, Garrison Unit, North Dakota. This slough has been classified as a type A: major slippage with movement onto the prism bottom. Photograph was taken in September 1991.

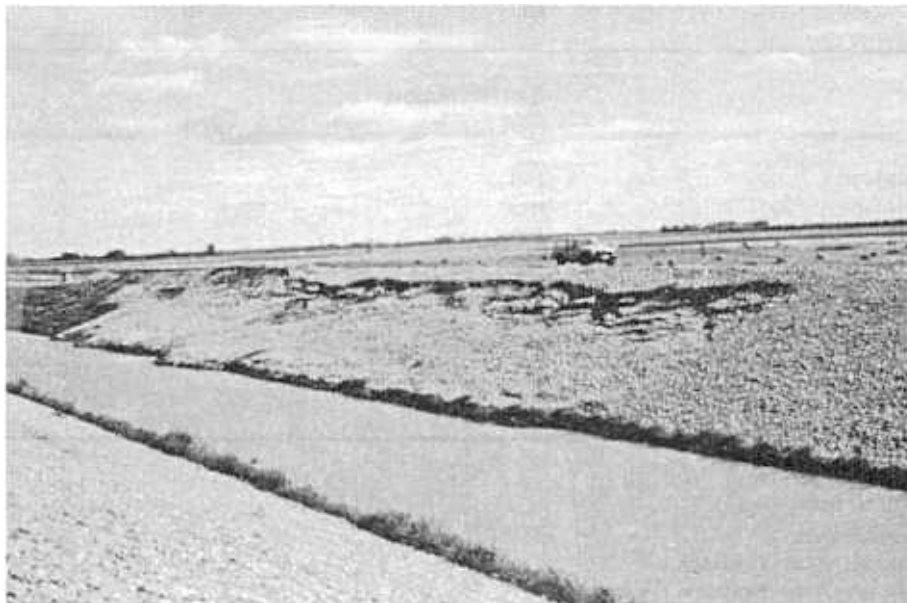


Figure 96. - View of protective soil cover slippage on New Rockford Canal, Reach 2. This slough has been classified as a type B: moderate slippage on the slopes only, bottom intact. Photograph was taken in September 1991.



Figure 97. - View of protective soil cover slippage on New Rockford Canal, Reach 2. This slough has been classified as a type C: minor slippage or crack opening. Photograph was taken in September 1991.

Canal Lining Demonstration Study, Upper Deschutes River Basin, Oregon

A canal lining demonstration study was initiated in 1991 on the Deschutes Project, Oregon, to evaluate various methods and materials for controlling seepage (Bureau of Reclamation, 1991a; 1991b). Most of the irrigation canals on this project are unlined and have been in service for over 40 years. Most of these canals divert water from the Deschutes River, near Bend, and traverse volcanic rock, which causes seepage rates to be high. As shown on figures 98 and 99, the canal subgrades are very rocky and present challenging preparation problems. These test sections will be monitored over a 10-year period to determine the life-cycle costs. The first in the series of durability reports was published after 2 years (Bureau of Reclamation, 1994c).

The Arnold Canal (a feature of the Arnold Irrigation District) and the North Unit Main Canal (a feature of the North Unit Irrigation District) were selected as sites for installation of the demonstration sections. To study the constructability of the alternative lining applications, the sections ranged from 150 to 300 m (500 to 1000 ft) in length. Proposed lining candidates are listed in table 25. A construction report details the actual types of lining used, installation techniques, pre- and post-construction seepage rates, and projected water savings (Bureau of Reclamation, 1994a).

This demonstration study is part of the Upper Deschutes River Basin Water Conservation project, which is a cooperative Federal/State effort by Reclamation and the Oregon Water Resources Department. The upper Deschutes River basin study area consists of the Deschutes River basin above Lake Billy Chinook, including the Crooked River basin, up to existing headwater storage reservoirs.



Figure 98. - View of rocky subgrade in North Unit Canal, Deschutes Project, Oregon. Such conditions present challenging preparation techniques for the installation of geomembranes.



Figure 99. - View of subgrade conditions in Arnold Canal, Deschutes Project, Oregon.

Table 25. - Potential lining candidates - Canal Lining Demonstration Study, Upper Deschutes River Basin, Oregon.

North Unit Irrigation District	
1. Polypropylene fiber shotcrete mix	
2. Steel fiber shotcrete mix	
3. Unreinforced shotcrete mix	
4. Pozzolan (fly ash)	
5. Urethane spray foam with urethan topcoat	
Arnold Irrigation District	
1. Structural, grout-filled mattress	
2. Reinforced bituminous geomembrane	
3. HDPE (high density polyethylene)	
4. HDPE with geotextile backing	
5. Polyolefin composite lining with shotcrete cover	
6. VLDPE (very low density polyethylene)	
7. VLDPE with shotcrete cover	
8. CSPE-R (reinforced chlorosulfonated polyethylene)/geotextile composite lining	

RESERVOIR APPLICATIONS

General

The majority of Reclamation's research investigating seepage control membranes has been associated with canals. Since the 1980s, lining technology has also been applied to reservoirs. In this section, the linings at Mount Elbert Forebay (Colorado), San Justo Reservoir (California), and Black Mountain Operating Reservoir (Arizona) are discussed.

Mount Elbert Forebay

Mt. Elbert Forebay was completed in March 1978 to provide water for Mt. Elbert Pumped-Storage Powerplant. By September 1978, observation well water levels along the reservoir's south ring rose in response to the initial filling. In 1979, Reclamation installed a geomembrane for reservoir seepage control because leakage through the reservoir's 1.5-m-thick compacted earth lining was threatening stability of the hillside between the reservoir and Mt. Elbert Powerplant. The geomembrane, installed in the summer of 1980, consisted of a 1.14-mm (45-mil) reinforced chlorinated polyethylene (CPE-R) material (figs. 100 to 102).

At the time, this installation constituted the world's largest single-cell geomembrane lining application to date at 117 ha (290 acres). To meet Reclamation's time schedule for power on-line, the installation had to be accomplished in one construction season.

The reservoir, located about 24 km (15 mi) southwest of Leadville, Colorado, impounds $14.2 \times 10^6 \text{ m}^3$ (1,150 acre-ft) of water, of which $8.8 \times 10^6 \text{ m}^3$ (700 acre-ft) are used to develop 200 MW of electrical power during peak demand. Maximum depth of the reservoir is 21 m (70 ft) with a weekly fluctuation of about 9 m (30 ft).

Details concerning the Mount Elbert installation may be found in Bureau of Reclamation (1981b) and Frobel and Gray (1984). The following three lining materials were specified as adequate materials for this reservoir lining: 1.14-mm (45-mil) CSPE-R (reinforced chlorosulfonated polyethylene), 1.14-mm (45-mil) CPE-R (reinforced chlorinated polyethylene), and 2.0-mm (80-mil) HDPE (high density polyethylene). The contractor selected a polymer blend of 49 percent CSPE-R and 51 percent CPE-R to meet the construction schedule.

Included in the specification for the work was a 5-year maintenance warranty period on the membrane lining. To monitor the performance of the lining during the warranty period and for long-term research purposes, a special test section was installed in the forebay reservoir. The 6- by 30-m (20- by 100-ft) test section was installed at a location within the reservoir that would allow periodic access for retrieval of the membrane lining test coupons.

To date, coupons were retrieved on a yearly basis for the first 5 years, in 1987 after 7 years of burial, and in 1990 after 10 years of burial (Morrison and Gray, 1991). The following physical and mechanical property tests are conducted on coupons to determine changes in the CPE-R sheet material and seams:

1. Weight
2. Mullen burst hydrostatic resistance (ASTM D 751-79, Method A)
3. Breaking strength (ASTM D 751-79, Grab Method A)
4. Ply adhesion (ASTM D 413-76, Machine Method Type A)



Figure 100. - Aerial view taken June 1980, looking south across the Mt. Elbert Forebay Reservoir. The first portion of placed geomembrane is visible in the near right side of the reservoir, and the processing plant is located in the center of the reservoir area. Also, the inlet-outlet structure (upper left-hand corner) forebay dam (foreground) slopes protection material around the perimeter of the reservoir and subgrade areas being prepared by the contractor.

5. Tear strength (ASTM D 751, Tongue Tear Method B)
6. Seam peel strength (ASTM D 1876-78)
7. Seam shear strength (ASTM D 751)
8. Large scale hydrostatic pressure resistance. The Mt Elbert evaluation tested coupon samples over a 10- to 12-mm aggregate subgrade at a hydrostatic head of 43 m, which was the same pressure used on samples of the unaged membrane lining material.

Original test specimens were taken from the same blanket as those used to fabricate the test section. Thus, results from extracted coupons can be compared directly with the test results obtained from the original blanket material. The original and test results from all of the coupons retrieved to date are reported in tables 26 to 29.

Results of studies conducted on the geomembrane installed in 1980 in the Mt. Elbert Forebay Reservoir indicate that the material is performing satisfactorily to date. Studies involve continuous monitoring of instrumentation on the hillside between the forebay reservoir and powerplant, and periodic retrieval of coupon samples from the field test section for laboratory testing and evaluation. In addition, laboratory water immersion test results are summarized in tables 30 and 31 and shown graphically on figure 103.

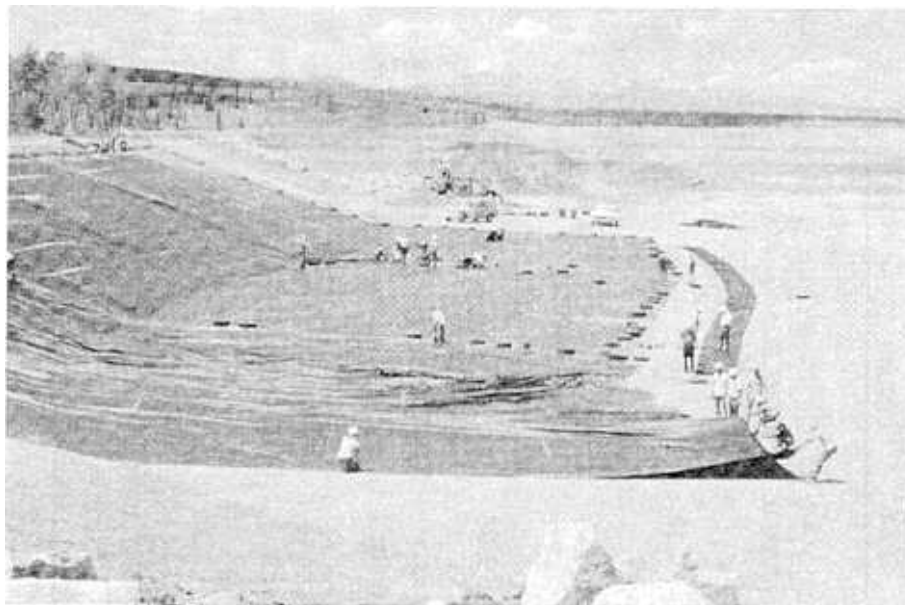


Figure 101. - Installation of geomembrane on reservoir side slopes at Mt. Elbert.



Figure 102. - Placement of protective soil material on geomembrane at Mt. Elbert.

Table 26. - Mt. Elbert test section results after one year of service.

Property	Hot Air Seam Panel			Dielectric Seam Panel		
	Original Data	1-yr Data (range)	% Change	Original Data	1-yr Data (range)	% Change
Weight Gain (%)			8.62			8.62
Mullen Burst (kPa)	2958.0	2868.3 2724-2930	-3.0	2764.9	2571.8 2482-2655	-7.0
Tear Strength (kN)	0.33	0.33 0.30-0.38	1.0	0.30	0.35 0.29-0.40	17.1
Ply Adhesion (kN/m)	1.59	1.28 1.21-1.33	-20.5	1.87	1.41 1.38-1.44	-24.8
Breaking Strength (kN)	1.26	1.33 1.21-1.40	4.9	1.26	1.25 1.18-1.30	-1.4
Bonded Seam Shear (kN)	1.33	0.90 0.82-0.97	-32.2	1.23	0.56 0.50-0.61	-54.1
Bonded Seam Peel (kN/M)	6.13	5.06 4.92-5.85	-17.4	6.92	6.06 5.83-6.20	-12.4
Adhesive Field Seam Shear (kN)	1.34	1.21** 1.15-1.26	-9.9	1.34	1.22* 1.16-1.30	-8.9
Adhesive Field Seam Peel (kN/m)	6.04	6.30 5.32-7.63	4.3	6.04	5.88 5.60-6.60	-2.6

* Field seam with cap strip

** Field seam without cap strip

*** Not required

Table 27 - Mt. Elbert test section results after three years of service.

Property	Hot Air Seam Panel			Dielectric Seam Panel		
	Original Data	1-yr Data (range)	% Change	Original Data	1-yr Data (range)	% Change
Weight Gain (%)			8.62			8.62
Mullen Burst (kPa)	2958.0	2868.3 2724-2930	-3.0	2764.9	2571.8 2482-2655	-7.0
Tear Strength (kN)	0.33	0.33 0.30-0.38	1.0	0.30	0.35 0.29-0.40	17.1
Ply Adhesion (kN/m)	1.59	1.28 1.21-1.33	-20.5	1.87	1.41 1.38-1.44	-24.8
Breaking Strength (kN)	1.26	1.33 1.21-1.40	4.9	1.26	1.25 1.18-1.30	-1.4
Bonded Seam Shear (kN)	1.33	0.90 0.82-0.97	-32.2	1.23	0.56 0.50-0.61	-54.1
Bonded Seam Peel (kN/M)	6.13	5.06 4.92-5.85	-17.4	6.92	6.06 5.83-6.20	-12.4
Adhesive Field Seam Shear (kN)	1.34	1.21** 1.15-1.26	-9.9	1.34	1.22* 1.16-1.30	-8.9
Adhesive Field Seam Peel (kN/m)	6.04	6.30 5.32-7.63	4.3	6.04	5.88* 5.60-6.60	-2.6

* Field seam with cap strip

** Field seam without cap strip

*** Not required

Table 28. - Mt. Elbert test section results after seven years of service.

Property	Hot Air Seam Panel			Dielectric Seam Panel		
	Original Data	1-yr Data (range)	% Change	Original Data	1-yr Data (range)	% Change
Weight Gain (%)			16.90			16.90
Mullen Burst (kPa)	2923.5	2840.7 2758-2965	-2.8	2985.5	2558.0 2248-2655	-14.3
Tear Strength (kN)	0.32	0.32 0.27-0.35	-1.6	0.31	0.27 0.26-0.28	-13.4
Ply Adhesion (kN/m)	1.61	1.24 1.21-1.28	-22.8	1.79	1.37 1.26-1.42	-23.5
Breaking Strength (kN)	1.26	0.91 0.77-1.17	-27.7	1.26	0.77 0.75-0.80	-38.7
Bonded Seam Shear (kN)	1.34	0.59 0.52-0.65	-55.9	1.21	0.49 0.48-0.50	-59.5
Bonded Seam Peel (kN/M)	6.06	3.38 3.22-3.59	-44.2	6.46	3.75 3.61-3.82	-42.0
Adhesive Field Seam Shear (kN)	1.34	1.17** 1.07-1.22	-12.6	1.34	1.09* 0.98-1.18	-18.3
Adhesive Field Seam Peel (kN/m)	6.04	6.51 5.71-7.20	7.8	6.04	7.74* 6.81-8.98	28.1

* Field seam with cap strip

** Field seam without cap strip

*** Not required

Table 29. - Mt. Elbert test section results after ten years of service.

Property	Hot Air Seam Panel			Dielectric Seam Panel		
	Original Data	1-yr Data (range)	% Change	Original Data	1-yr Data (range)	% Change
Weight Gain (%)			ND			ND
Mullen Burst (kPa)	2923.5	2392.6 2344-2448	-18.2	2895.9	2302.9 2275-2379	-20.5
Tear Strength (kN)	0.29	0.30 0.27-0.33	1.1	0.33	0.29 0.27-0.31	-12.8
Ply Adhesion (kN/m)	1.54	1.47 1.44-1.52	-4.2	1.77	1.65 1.58-1.75	-6.9
Breaking Strength (kN)	1.26	1.01 0.89-1.10	-20.3	1.26	0.89 0.69-1.06	-29.3
Bonded Seam Shear (kN)	1.28	0.78 0.74-0.81	-39.3	1.16	0.55 0.51-0.58	-52.8
Bonded Seam Peel (kN/M)	5.38	4.41 3.87-5.03	-17.9	7.84	3.61 3.40-3.73	-54.0
Adhesive Field Seam Shear (kN)	1.34	1.18** 1.09-1.27	-12.0	1.34	1.09* 1.00-1.13	-18.6
Adhesive Field Seam Peel (kN/m)	6.04	5.46 4.66-6.69	-9.6	6.04	6.09* 4.52-8.12	0.9

* Field seam with cap strip

** Field seam without cap strip

*** Not required

Table 30. - Water immersion test results - 1.14-mm (45-mil) CPE-R.

Property	Original data (range)	One year data (range)	Percent change	Three year data (range)	Percent change	Five year data (range)	Percent change
Weight Gain (percent)			15.58		19.25		21.07
Mullen burst (kPa)	2909.7 (2448-3075)	2330.5 (2275-2413)	-19.9	2706.3 (2551-2861)	-7.0	2526.3 (2344-2655)	-13.2
Tear strength (kN)	0.35 (0.24-0.44)	0.43 (0.41-0.44)	20.2	0.43 (0.42-0.43)	20.3	0.37 (0.35-0.40)	5.1
Ply adhesion (kN/m)	1.54 (1.31-1.73)	1.24 (1.19-1.30)	-19.3	1.51 (1.47-1.54)	-2.3	1.38 (1.33-1.42)	-10.2
Hot Air seam shear (kN)	1.19 (0.89-1.37)	0.61 (0.60-0.63)	-48.7	0.93 (0.89-0.97)	-22.1	0.60 (0.60-0.60)	-49.3
Hot Air seam peel (kN/m)	5.50 (4.64-6.81)	4.82 (4.52-5.06)	-12.4	6.01 (5.78-6.22)	9.2	3.64 (3.57-3.69)	-33.8
Dielectric seam shear (kN)	1.30 (1.00-1.41)	0.64 (0.62-0.66)	-51.0	0.89 (0.89-0.89)	-31.7	0.77 (0.77-0.77)	-40.6
Dielectric seam peel (kN/m)	6.74 (6.01-7.49)	5.80 (5.69-5.92)	-14.0	4.11 (3.94-4.20)	-39.0	4.10 (3.96-4.25)	-39.2
Adhesive seam shear (kN)	1.23 (1.21-1.25)	1.15 (1.12-1.18)	-6.5	1.32 (1.29-1.36)	7.4	1.20 (1.14-1.25)	-2.7
Adhesive seam peel (kN/m)	5.38 (4.01-7.41)	5.22 (4.76-6.13)	-2.9	6.02 (5.60-6.30)	12.1	5.24 (4.69-5.69)	-2.6

Table 31. - Water immersion test results - 0.50-mm (20-mil) CPE.

Longitudinal test direction							
Property	Original data	One year		Three year		Five Year	
		Test value	Percent change	Test value	Percent change	Test value	Percent change
Weight gain (percent)			16.9		20.4		20.9
Tensile Strength (kN/m)	6.39	5.76	-9.9	5.59	-12.6	5.39	-15.6
Elongation (percent)	490.0	492.0	0.4	498.0	1.6	493.0	0.6
Modulus (kN/m)	1.91	0.93	-51.4	1.24	-34.9	1.63	-14.7
Tear strength (N)	18.68	12.01	-35.7	12.01	-35.7	15.57	-16.7
Transverse test direction							
Weight gain (percent)			16.9		20.4		20.9
Tensile Strength (kN/m)	5.53	4.78	-13.6	4.59	-17.1	4.47	-19.3
Elongation (percent)	587.0	587.0	0.0	581.0	-1.0	568.0	-3.2
Modulus (kN/m)	1.49	0.93	-37.6	0.91	-38.8	1.17	-21.2
Tear strength (N)	18.24	13.79	-24.4	14.23	-22.0	17.35	-4.9

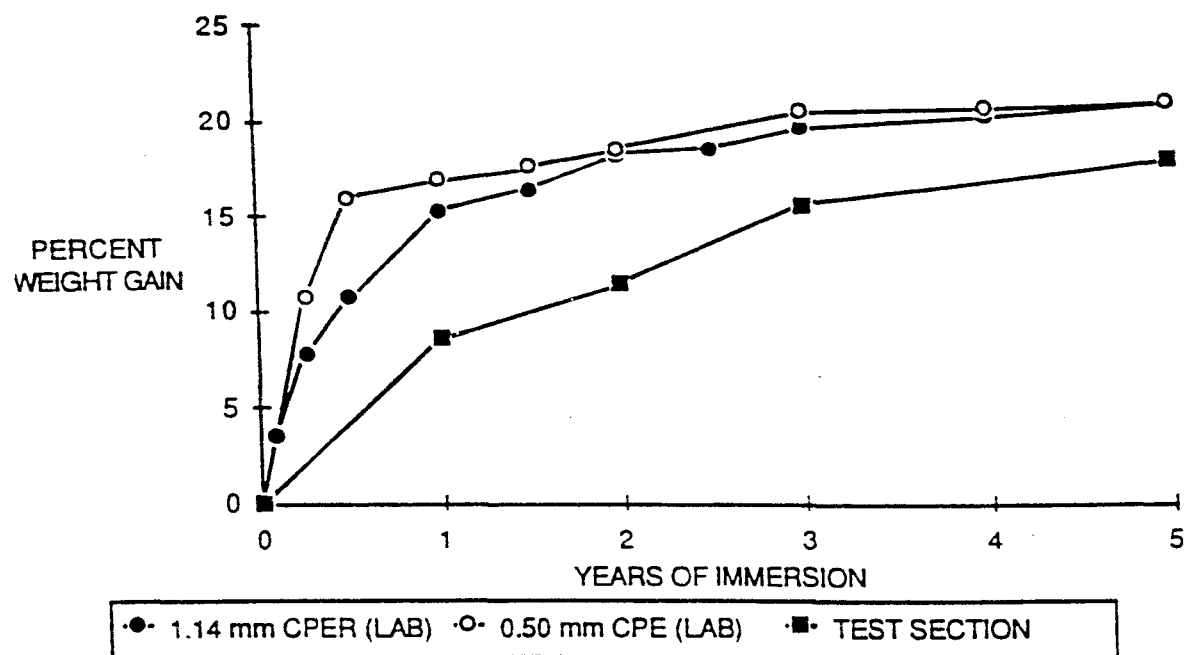


Figure 103. - Moisture absorption - laboratory water immersion testing and Mt. Elbert test section results.

San Justo Reservoir

San Justo Reservoir near Hollister, California, was constructed by Reclamation in 1985 as an off-stream storage facility to provide water for irrigation and municipal purposes. The reservoir, shown on figure 104, is formed by two earthfill structures: a dam to the west and a dike to the north.

Several large beds of sand are located within the reservoir site. In addition to the loss of water, the increased seepage through the sand beds could increase the potential for landslides on the downstream portions of natural ridges which enclose the reservoir. Thus, the decision was made to install a soil-covered geomembrane over sloping portions of the reservoir containing the impervious sand beds. In flatter areas where natural impervious soil covers the sand beds, a supplemental 2-m-thick earthfill blanket of clay was placed instead of the membrane lining.

The following geomembranes were included as options in the specifications: 1.0-mm (40-mil) HDPE-A (high density polyethylene-alloy), 0.91-mm (36-mil) CPE-R, 0.91-mm (36-mil) CSPE-R, and 1.14-mm (45-mil) PVC. The contractor selected the HDPE-A geomembrane.

About 190,000 m² (47 acres) of geomembrane were installed for seepage control at 6 locations within the reservoir. An aerial view of several of these sites is shown on figure 105.



Figure 104. - Aerial view of San Justo Reservoir. Several large beds of clean sand can be seen within the reservoir.

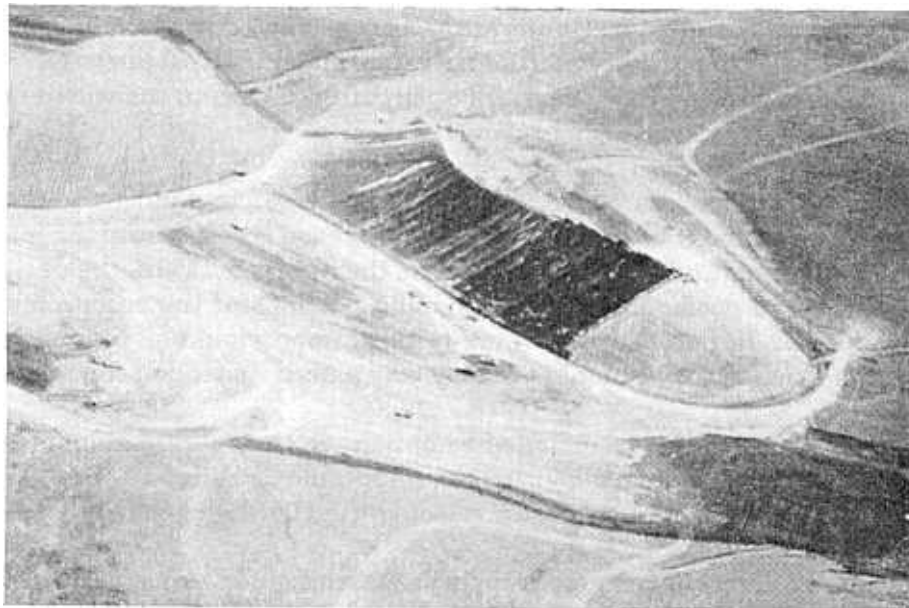


Figure 105. - Aerial view showing installation of geomembrane at several sites within the San Justo Reservoir.

The HDPE-A liner was manufactured in rolls about 6 m (20 ft) wide by 200 m (650 ft) in length. The roll goods were shipped to the job site, where they were unrolled on the prepared subgrade as shown on figure 106. They were then joined using extrusion fillet welding as shown on figure 107. The geomembrane was secured at the toe and top of the slope in a v-shaped anchor trench.

At installation, the thermal expansion of the geomembrane caused waviness, which led to some permanent folds in the liner when the protective soil cover was placed. This condition is shown on figure 108. Folded samples were included in the coupon monitoring section to determine the long-term effect of the creases on the performance of the geomembrane.

In 1990, an additional 6100 m² (1.5 acres) of geomembrane were installed over another sand lens in the bottom of the reservoir. For this work, a 1.5-mm (60-mil) HDPE geomembrane was used because HDPE-A was no longer being manufactured.

In 1986, an unusually heavy rainfall resulted in slippage of several portions of the protective soil cover (shown on fig. 109). In general, failures occurred on slopes steeper than 4H:1V.

To support analytical studies and to aid in designing an acceptable remedial modification, a laboratory test program was undertaken to determine the frictional resistance of the soil on the geomembrane (Morrison et al., 1991). Samples of various types of soils and geomembranes were tested in a 100- by 100-mm (4- by 4-in) direct shear apparatus.



Figure 106. - Unrolling HDPE-A geomembrane liner was produced in rolls about 6 m wide by 200 m long.

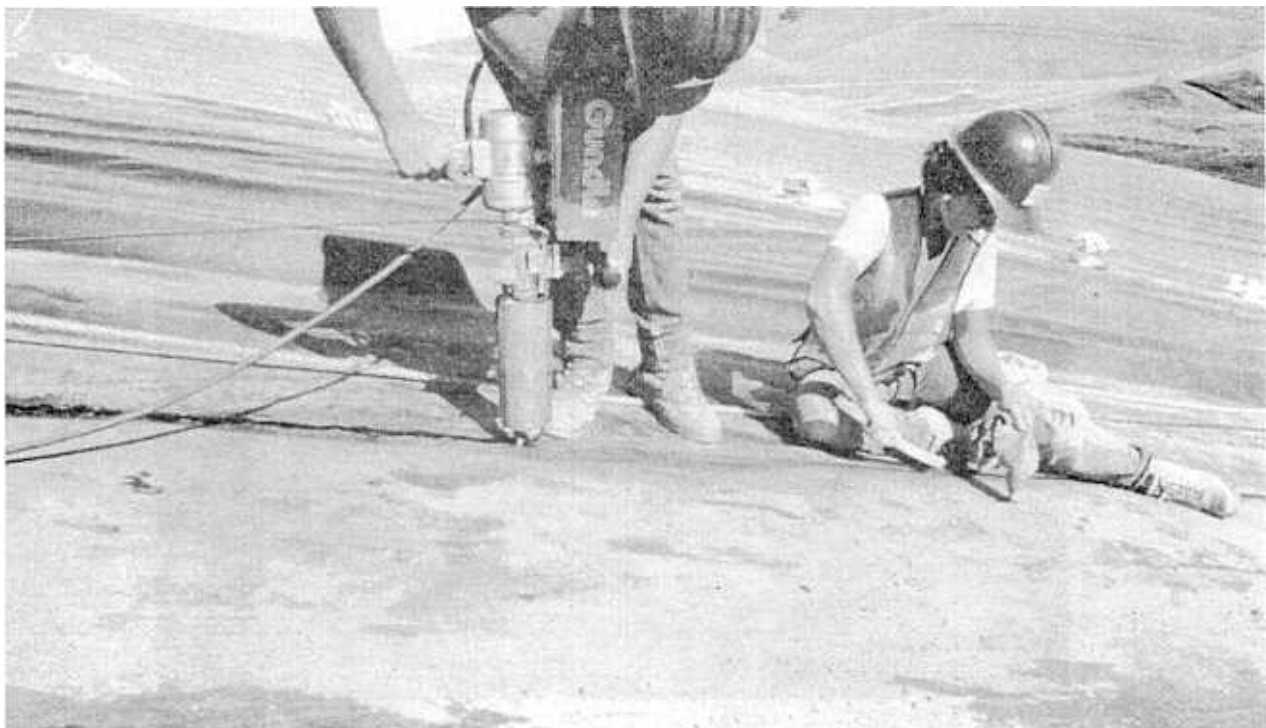


Figure 107. - Field seaming geomembrane using a hot-extruded fillet weld. Worker at right is cleaning and wire brushing overlapped area to be seamed.

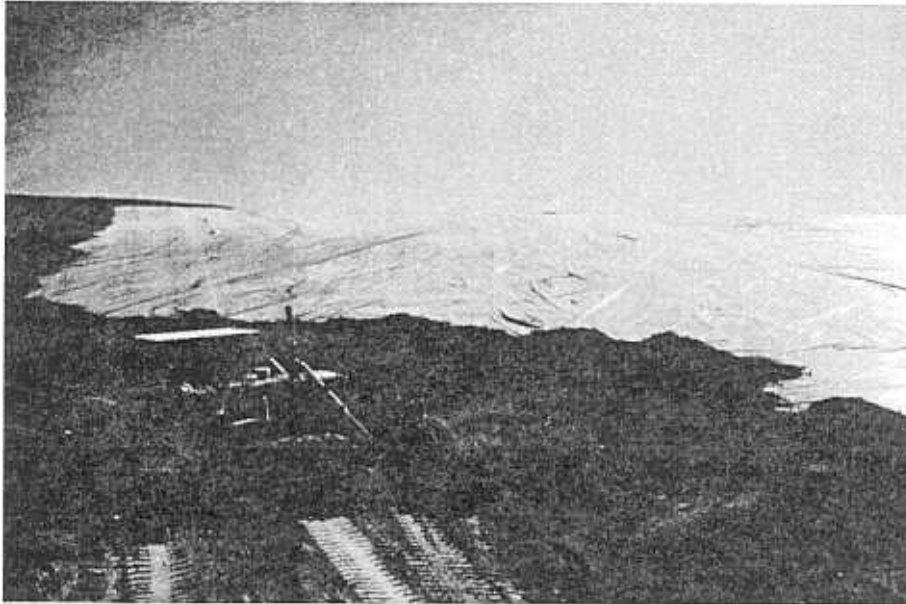


Figure 108. - Waviness led to some permanent folds in geomembrane after protective soil cover was placed.



Figure 109. - View showing slippage of protective soil cover.

Geomembrane materials tested included:

1. Original material (smooth)
2. Original material scored with a wire brush
3. Original material sandblasted
4. Textured material
5. Original material with an attached geogrid

Soil materials used in the test included the original material covering the membrane (soil A), material representing the sand underlying the membrane (soil C), and materials representing proposed cover materials (soils B₁ and B₂).

The results of the testing are shown in table 32. Included in the table are some of the details of the test apparatus and test procedures. Using these test results, stability analyses were completed and indicated that all of the modified geomembranes demonstrated an improved friction angle and would be stable on the slopes under the loadings imposed. The analyses also indicated that a thicker cover material generally lowered the factor of safety.

During the summer of 1987, a remedial construction program was initiated to repair the exposed areas of geomembrane. Seven of the 8 areas were repaired by sandblasting the top surface of the exposed liner to enhance the frictional resistance, followed by covering it with a 0.15-m (6-in) layer of pervious sand and gravel bedding and a 0.3-m (12-in) layer of cobbles. For the remaining slide area, the existing geomembrane was removed and replaced with a textured HDPE geomembrane and covered with bedding and cobbles.

To monitor the performance of the geomembrane, a coupon monitoring section was installed in the reservoir. Results of coupon testing at origin, 2 years, and 5 years are summarized in table 33.

Additional information on the aging characteristics of the San Justo geomembrane was obtained in a laboratory test conducted on random samples of HDPE-A lining. Both folded and unfolded tensile and tear specimens were subjected to the following aging conditions:

1. Room temperature (23 °C, 50 percent relative humidity)
2. 37 °C oven aging
3. Water immersion in Denver laboratory tap water. The temperature of running tap water varied between 10 and 15 °C during the immersion period.

The laboratory aging study was conducted for 5 years, and the tensile and tear specimens were removed and tested on a yearly basis. Test results are summarized in table 34. These results indicated that, similar to the field samples, very little change occurred in tensile and tear strength properties. Also, the samples exhibited no adverse effect from being folded.

Table 32. - Results of interface friction tests.

Soil	Friction resistance						Soil only
	Smooth	Sandblasted	Wire brush	Geogrid	Texturized	Embossed	
A (wet)	N/A (19°)	(1) 28° (28°)	28° (30°)				
B ₁		30° (31°)		32° (36°)	32° (36°)		33° (39°)
B ₂		26° (26°)	28° (29°)			32° (32°)	38° (38°)
C (wet)	21° (21°)	28° (28°)					
(moist)	20° (22°)						
(dry)	26° (29°)						

(1) Values are given for large strain and peak (parenthesis) results. Values at large strain were used for analyses except where unavailable (N/A).

(2) Test results using direct shear apparatus on soil only.

Testing details: Shear box size - 4 inch x 4 inch
Time of saturation - 1 to 3 days
Normal applied pressure - 2, 5, 10 psi
Placement densities - 40 to 60% relative density
Strain rate - 0.005 inch/minute

*Classification

A	CL
B ₁	SP-SM
B ₂	SP
C	SW-SM

Table 33. - Test results for San Justo geomembrane coupon samples.

Property	Original data	2-year data	5-year data
Tear resistance, lbf (folded)	---	26.1	32.9
Tear resistance, lbf (unfolded) L	36.8	26.6	31.3
T	33.7	29.2	34.6
Breaking strength, lbf/in. (folded)	---	113	155
Ultimate elongation, % (folded)	---	671	679
Breaking strength, lbf/in. (unfolded) L	199	141	189
T	197	152	177
Ultimate elongation % (unfolded) L	774	739	790
T	---	---	---
Seam shear strength, lb/in	---	97	116
Seam peel strength, lb/in	---	85	96

Table 34. - Results of laboratory aging studies conducted on San Justo geomembrane.

Test Duration	Test Conditions 73°F, 50% RH						Test Condition Water Immersion						Test Condition Heat aging at 100 °F					
	Tear strength, lbf		Breaking Strength lbf/in		Ultimate Elongation, %		Tear strength, lbf		Breaking strength lbf/in		Ultimate Elongation, %		Tear strength, lbf		Breaking strength lbf/in		Ultimate Elongation, %	
	F	U	F	U	F	U	F	U	F	U	F	U	F	U	F	U	F	U
Original	---	31.8	---	199	---	774	---	31.8	---	199	---	774	---	31.8	---	199	---	774
52 weeks	32.2	32.7	198	196	836	800	33.0	32.0	201	199	818	785	32.4	33.4	206	204	833	813
104 weeks	31.5	28.6	210	191	788	788	32.5	32.2	200	216	818	840	33.6	33.8	198	191	827	784
156 weeks	32.5	34.4	200	209	806	810	33.3	32.9	199	184	811	803	34.7	33.4	203	203	832	846
208 weeks	34.2	33.9	191	213	785	831	34.5	32.2	204	208	802	815	34.1	35.6	193	202	779	829
260 weeks	33.9	34.1	192	196	817	783	33.9	35.9	192	205	798	808	34.5	35.6	210	204	858	808

F denotes - folded

U denotes - unfolded

Black Mountain Operating Reservoir

In the summer of 1990, about 9.3 hectares (23 acres) of 1.14-mm (45-mil) PVC geomembrane were used to line the Black Mountain Operating Reservoir. This facility is a new water-regulating/storage reservoir located about 14.5 kilometers (9 miles) southwest of Tucson, Arizona. The geomembrane watertight lining was part of the design to allow for rapid drawdown conditions which might occur when providing sufficient water to the Black Mountain pumping plant.

The geomembrane was anchored at the top of the side slopes in a v-shaped soil trench and at concrete structures by a solvent weld to an embedded PVC anchor strip. On the 3H:1V side slopes, a geotextile was used to provide protection for the geomembrane during placement of riprap on the side slopes. To protect the PVC during cleaning operations, the bottom of the reservoir was covered with a 150-mm (6-inch) thick layer of unreinforced concrete.

An aerial view of the Black Mountain Operating Reservoir after lining is shown on figure 110. A laboratory test program examining the puncture behavior of PVC under concrete with a load showed no failures under the test conditions examined (Comer and Straubinger, 1993).



Figure 110. - Aerial view of the Black Mountain Operating Reservoir after lining.

DAM REHABILITATION APPLICATIONS

Emergency Spillway - Cottonwood Dam No. 5

In 1981, an 80-m (250-ft) long flexible membrane lining was installed on a spillway of an earth dam near Grand Junction, Colorado. The rehabilitation of Cottonwood Dam No. 5 offered an excellent opportunity for a field study. The study used a geomembrane as a watertight barrier to protect the embankment from erosion in the event of overtopping.

The field test installation was completed in the fall of 1985, and an operational test, as shown on figure 111, was conducted in 1986. The geomembrane, a 0.9-mm (36-mil) thick Hypalon (CSPE-R), performed as expected—quite well. During the initial flows over the spillway, the soil cover was washed away until the membrane on the bottom of the spillway was exposed. Even though the flow carried much abrasive material, stones, and a few cobbles about 100 mm (4 in) in diameter, little or no erosion or damage of the membrane was observed. The results of this study are discussed in Bureau of Reclamation report "Emergency Spillways Using Geomembranes" (1988d).



Figure 11 View of exposed membrane after field test of emergency spillway, Cottonwood Dam No. 5.

Raised Embankment - Pactola Dam

The Safety of Dams modification for Pactola Dam required raising the crest of the earth and rockfill embankment and enlarging the spillway. To reduce the number of construction seasons, to handle heavy seasonal tourist traffic, and to minimize borrow area development, a geomembrane was chosen as the impervious barrier for the raised embankment.

To evaluate the likelihood of puncturing the geomembrane and to aid in final material selection, Reclamation developed a laboratory testing program. Four membranes, a 0.75-mm (30-mil) PVC, a 0.9-mm (36-mil) CSPE-R, and 1-mm (40-mil) and 2-mm (80-mil) HDPE were initially selected for investigation using the Reclamation hydrostatic pressure cells. The testing program, conducted over three subgrade conditions, also included use of various geotextile backings to evaluate if such treatment would increase puncture resistance (Morrison, 1984). Results of the testing led to the specification of either 1-mm (40-mil) HDPE or 1.1-mm (45-mil) CSPE-R, with a non-woven geotextile.

A 1-mm (40-mil) HDPE membrane, in conjunction with a non-woven geotextile, was embedded within the embankment. Figure 112 shows the installation. Details of the installation may be found in "Technical Report Pactola Dam Modification," prepared for the Safety of Dams Program by the Missouri Basin Region (Bureau of Reclamation, 1988e). This installation was Reclamation's first use of a geomembrane as the impervious barrier for a storage reservoir embankment. In this case, expected maximum loading conditions were not severe (routing of the PMF [probable maximum flood] through the enlarged spillway might result in the water surface rising against the membrane for six hours, with a maximum head of 5 m [16 feet]), and may never be imposed because of the low probability of a major flood event occurring.



Figure 112. - Installation of 1-mm HDPE within embankment at Pactola Dam

Seepage Control

Ochoco Dam, Oregon.-Ochoco Dam, situated about 10 km (6 mi) east of Prineville in Crook County, Oregon, was originally constructed between 1917 and 1920 using hydraulic fill methods. Seepage problems led to modification of the dam and structural features in 1949 and 1950. In 1989, changes in seepage volumes, piping of sand and gravel through the toe drains, and increases in piezometric pressures near the right abutment foundation/embankment contact resulted in a re-evaluation of the existing conditions at the dam (Bureau of Reclamation, 1990).

In January 1991, about 23,900 m² (180,000 ft²) of 2-mm (80-mil) textured HDPE were installed on the upstream right abutment of the dam. Figure 113 shows this installation. Several areas of the right abutment were identified to be sinkholes. At these locations, an underlying needle-punched, non-woven geotextile was installed to minimize the effects of differential settlement on the geomembrane.

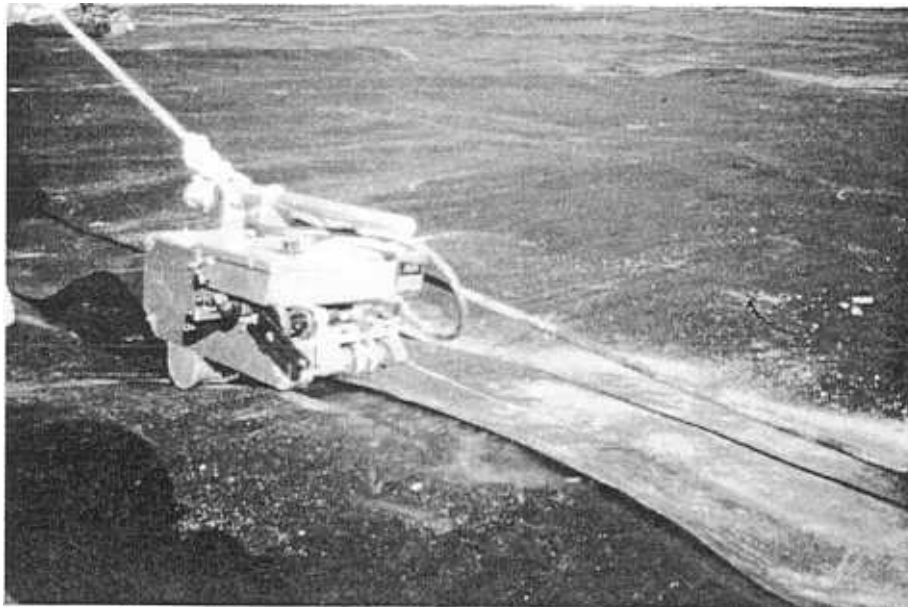


Figure 113. - Installation of textured 2-mm HDPE geomembrane at Ochoco Dam in Oregon.

Black Lake Dam, Montana.-Located along the Jocko River in northwestern Montana, within the boundaries of the Flathead Indian Reservation, Black Lake Dam is founded on an ancient, inactive landslide. Deposits of several different geologic materials (talus and interfingering alluvial and colluvial deposits) lie beneath the landslide. Although each type of material is discontinuous, they are thought to provide a direct path for seepage from the reservoir through the right abutment of the dam.

A partial upstream geomembrane liner was selected as the preferred construction alternative to mitigate seepage-related safety of dams deficiencies at Black Lake. Laboratory "performance" testing of various geomembrane and geomembrane/geotextile composite materials was performed to determine the most suitable construction materials to use (Bureau of Reclamation, 1991c; Comer and Dewey, 1995).

Testing results showed that 1-mm (40-mil) VLDPE/geotextile had the properties needed for this repair. To increase the factor of safety, the actual geomembrane used was 1.5-mm (60-mil) VLDPE/geotextile. The installation at Black Lake is shown on figure 114. Property values for the original material and resin are summarized in tables 35a and 35b.



Figure 114. - Installation of textured 1.5-mm VLDPE at Black Lake Dam, Montana.

Table 35a. - Black Lake Dam VLDPE resin properties.

Property	Test method	Requirements
Density (g/cm ³) minimum	ASTM D 792 or ASTM D 1505	0.897-0.912 g/cm ³
Melt Index(g/10 min.), maximum	ASTM D 1238 condition E	1.1 g/10 min

Table 35b. - Black Lake Dam textured VLDPE geomembrane physical properties.

Table 35b. - Black Lake Dam Textured VLDPE geomembrane physical properties

Property	Test method	Requirements*
Thickness (mils)	ASTM D 374, 751, 1593	
Minimum average		60 mils
Lowest individual		54 mils
Density (g/cm ³)	ASTM D 1505	
Minimum		0.900 g/cm ³
Maximum		0.945 g/cm ³
Meltflow index (g/10 min.), maximum	ASTM D 1505, Condition E	1.1 g/10 min.
Tensile Properties, minimum:	ASTM D 638 Type IV at 20 in/min.	
1. Tensile strength at break (lb/in)		63 lb/in
2. Elongation at break (percent). (2-inch gauge length)		300 percent
Tear resistance (lb)	ASTM D 1004, Die C	20 lb
Puncture resistance (lb)	FTMS** 101, Method 2065	45 lb
Dimensional stability (percent)	ASTM D 1204(as modified in NSF 54)	plus or minus 3 percent
Total ash content	ASTM D 1506	less than 5 percent
Carbon black content (percent)	ASTM D 1603	2.0 to 3.0 percent
Carbon black dispersion acceptable levels	ASTM D 3015 (as modified in NSF 54)	A1, A2, B1
Low temperature impact (°C)	ASTM D 746	-60 °C
Seam properties***, minimum:	ASTM D 4437 (NSF*** modified)	
1. Shear strength (lb/in)		60 lb/in
2. Peel adhesion (lb/in)		54 lb/in

* Unless otherwise indicated, required values will be minimum average roll values.

** Federal Test Method Standards. Available for purchase.

*** All seams shall demonstrate a film tearing bond (FTB), which is failure in the ductile mode of one of the bonded sheets by tearing prior to complete separation of the bonded area during seam testing.

**** National Sanitation Foundation (NSF).

Pablo Dam, Montana. Pablo Dam is located 5 km (3 mi) south of Polson and 5 km (3 mi) north of Pablo, Montana. A geomembrane was selected as a cost effective option to replace the upstream face of Pablo Dam (Bureau of Reclamation, December 1992b). Figure 115 shows installation of the geomembrane at Pablo. For this repair, either an HDPE or VLDPE textured membrane was specified. The contractor selected a 1.5-mm (60-mil) coextruded textured HDPE geomembrane. This lining was installed in the winter of 1993.

Because of their ability to conform with the subgrade, resistance to environmental stress cracking, and excellent elongation properties, VLDPE, LLDPE, or PP will most likely be selected for future winter dam modifications. The stiffer HDPE used at Pablo was not as easy to install as the VLDPE used at Black Lake.



Figure 115. - Installation of textured 1.5-mm (60-mil) HDPE at Pablo Dam, Montana.

SPECIAL APPLICATIONS

Geomembranes are also being evaluated for special applications such, as:

1. Exposed linings
2. Rehabilitation of deteriorated concrete linings
3. Underwater lining of operating canals
4. Bottom-only linings in soils where the seepage is primarily in the vertical direction
5. Barriers for drainage systems

Exposed Linings

A study was initiated under the OCCS Program to evaluate the use of exposed flexible membranes as alternatives to concrete and buried plastic linings in Reclamation's irrigation canal work. Because much of the cost of buried plastic lining involves overexcavation and placement of the cover material, an exposed GM liner offers significant cost savings. Potential lining candidates that are UV resistant include CSPE-R (reinforced chlorosulfonated polyethylene), CPE-R (reinforced chlorinated polyethylene), EPDM (ethylene propylene diene monomer), HDPE (high density polyethylene), and EIA (ethylene interpolymer alloy).

Reclamation now occasionally specifies exposed geomembranes in new construction, especially in small hydraulic structures such as settling basins, retention ponds, and solar ponds. The invert is typically covered with soil to anchor the liner against wind uplift.

Potential advantages of exposed geomembranes over buried plastic linings include:

1. Canal side slopes can be increased to 1.5:1 or even 1:1, subsequently saving costs in reduced excavation and right-of-way.
2. Protective soil cover on the canal side slopes becomes unnecessary.
3. Undetected damage to a geomembrane is minimized.
4. Lining replacement, if required, is easier.

Disadvantages and potential problem areas that are always present with any new system should be studied thoroughly. Exposed membrane linings (side slopes only) can be subjected to the following adverse conditions:

1. Wind and water forces
2. Possibility of vandalism
3. Possibility of animal damage
4. Minor ultraviolet surface degradation over time
5. Abrasion

Several exposed geomembrane canal installations are now in operation. Three of these are:

1. A 240-m (800-ft) long test section of 0.75-mm (30-mil) HDPE was installed in the Whiterock Extension Canal, Bostwick Division, Kansas, in May 1983. This canal was unlined and had experienced some embankment failure near milepost 12.5, which is in sandy soil. The installation between station 743+75 and 751+75 is shown on figures 116 to 120. Equipment and labor for the installation were furnished by the local irrigation district, and the manufacturer donated the HDPE material.

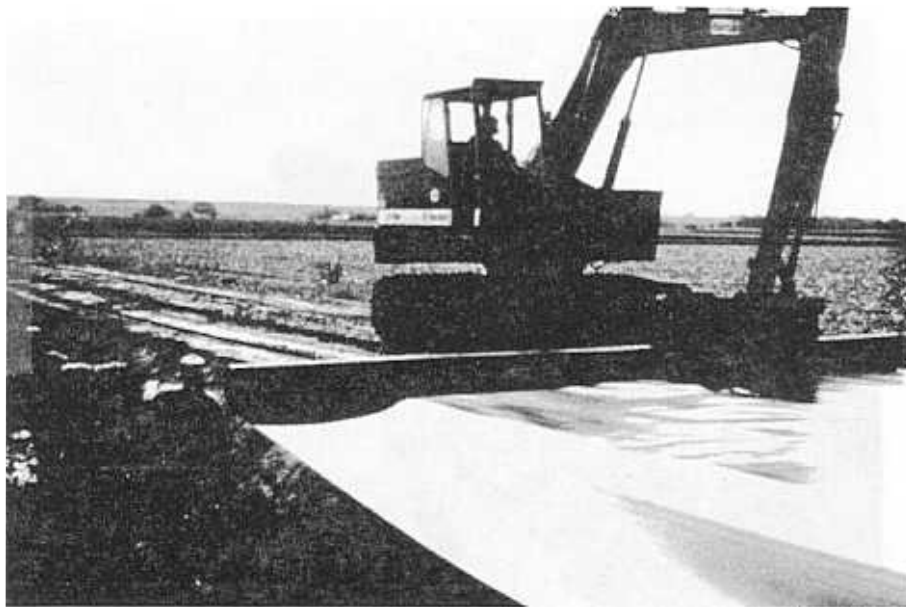


Figure 116. - View of unrolling 0.75-mm (30-mil) HDPE geomembrane for installation in Whiterock Extension Canal, Courtland Unit, Kansas.



Figure 117. - Another view of unrolling HDPE geomembrane. The geomembrane was supplied in one sheet 244 m (800 ft) in length by 6.86 m (22.5 ft) wide.



Figure 118. - Positioning HDPE geomembrane for installation in Whiterock Extension Canal. Note anchor trench at right side of photograph.



Figure 119. - Another view showing the positioning of the HDPE geomembrane in the Whiterock Extension Canal.



Figure 120. - View of completed HDPE geomembrane installation on Whiterock Extension Canal. Side slopes will be left exposed.

Field inspections were made in 1985 (Frobel, 1983) and 1991 (Bureau of Reclamation, 1986b) after 8 years of service. Photographs taken during the latter inspection are shown on figures 121 to 123. Several folds and creases were examined, and no membrane deterioration was noted. The membrane appeared to be in good condition.

The field reported (Reclamation, 1992a) that the exposed geomembrane is performing satisfactorily after 8 years. Small holes believed to have been caused by deer were noted (figs. 124 and 125). Membrane tautness and undulations in the subgrade surface appear to indicate that the membrane has "bridged" across depressions or voids in the subgrade. Each hole appeared to have a void behind the membrane. The depression or void may have been caused either by the initial subgrade surface or by subsequent settlement caused by saturation from water leaking through the holes.

2. The Kennewick Irrigation District in Washington installed a reinforced, rubberized, bituminous geomembrane in 1987. About 1490 m² (16,000 ft²) of liner were placed in the Kennewick Main Canal and Badger East Lateral. Installation information can be found in Weatherly (1989). The Kennewick Irrigation District engineer reported in February 1992 that the geomembrane had experienced some delamination.

3. The Lugert-Altus Irrigation District in southwestern Oklahoma installed a different polymer-modified bituminous liner on the W.C. Austin Project, West Canal, in May 1994. The 120-mm (4800 mil) thick polyester reinforced liner was applied in the canal bed for 0.8 km (0.5 mi). Installation information can be found in Provine (1994).



Figure 121. - View of test section of HDPE geomembrane in White Rock Extension Canal after 8 years of service. Photograph was taken May 29, 1991.



Figure 122. - Another view of test section shown on figure 121



Figure 123. - Small hole in left side of test section of HDPE geomembrane. Photograph was taken May 29, 1991



Figure 124. - Small hole and slits in left side of test section of HDPE geomembrane. Slits appear to have been caused by deer hooves. Photograph was taken May 29, 1991.



Figure 125. - Tears in HDPE geomembrane (right side) occurred during installation in 1983. Repairs made at the time of installation failed shortly after being made and no additional repairs have been attempted to date. Photograph was taken May 29, 1991.

Rehabilitation of Concrete Lining

Reclamation has over 8,000 km (5,000 mi) of concrete-lined canals and laterals in operation. The condition of these conveyance systems varies depending upon age, climatic conditions, and O&M (operation and maintenance) history.

Generally, the time for repair of these facilities is restricted to the nonirrigation season, or is limited to a short duration because of water delivery commitments. The use of geomembranes for some of the repair work appears to be an expedient and viable method. Three case histories are presented below:

1. Mirdan Canal. - In July 1987, a bank failure occurred in the Mirdan Canal, Upper Loup Division, Nebraska, resulting in a total loss of the canal flow (fig. 126). The failure, near station 685+00, was caused by saturation and subsequent settlement of low density, silty subgrade soils. The saturation was caused by leakage through frost-induced cracks in the concrete lining as shown on figure 127.

To put the canal back into operation, a temporary bypass channel was built around the damaged lining (fig. 128) and was lined with PVC (fig. 129). For permanent repair, specifications (Bureau of Reclamation, 1987b) were prepared and issued to cover the following items:

- a. Removal of damaged concrete
- b. Subgrade preparation, which entailed maintaining the original 1.5:1 side slopes (fig. 130)
- c. Installation of a 1.0-mm (40-mil) HDPE liner
- d. Installation of a fabric form concrete protective revetment on the side slopes and a gravel cover in the canal invert.

About 400 m (1500 ft) of the canal were reconstructed in three separate reaches under the specifications. This repair included the damaged area as well as two other problem sites. The construction sequence for the repair work is shown on figures 130 to 136. In 1988, another specification (Bureau of Reclamation, 1988c) was issued to repair an additional 150 m (500 ft) of existing canal. For this work, 0.75-mm (30-mil) PVC was used instead of the 1.0-mm (40-mil) HDPE material.

Field personnel reported in February 1992 that the performance of the repair has been satisfactory, and no maintenance or operational problems have occurred with the membrane. Because the bottom is usually covered with water, visual inspection of the gravel cover material has not been made.

Concrete shrinkage cracks in the concrete revetment on the sides have taken place, but the concrete serves only to protect the membrane liner and does not function as a seepage barrier. Water migrating through the concrete can escape through the weep/drain valves that are in place in the fabric formed concrete.



Figure 126. - Failure of Mirdan Canal, North Loup Division, Nebraska. The failure, near station 685+00, was caused by saturation and subsequent settlement of the low density, silty subgrade soils. The saturation was caused by leakage through frost-induced cracks in the concrete lining as shown on figure 127. Photograph taken July 1987.



Figure 127. - Cracks in concrete lining in Mirdan Canal caused by frost heave.



Figure 128. - To put the Mirdan Canal back into operation, a temporary bypass channel was built around the damaged lining.



Figure 129. - View of temporary bypass channel for Mirdan Canal lined with 0.5-mm (20-mil) PVC geomembrane.



Figure 130. - Repair of Mirdan Canal. Damaged concrete was removed and subgrade was prepared, retaining the 1.5 (H):1(V) side slopes.

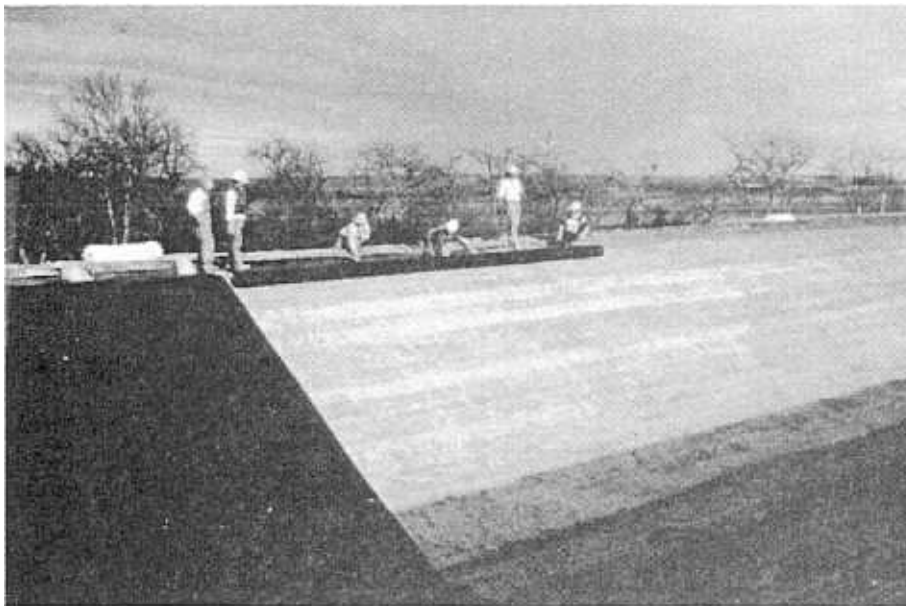


Figure 131. - Installation of 1.0-mm (40-mil) HDPE geomembrane in Mirdan Canal. Material was furnished in rolls about 10 m (33 ft) wide.

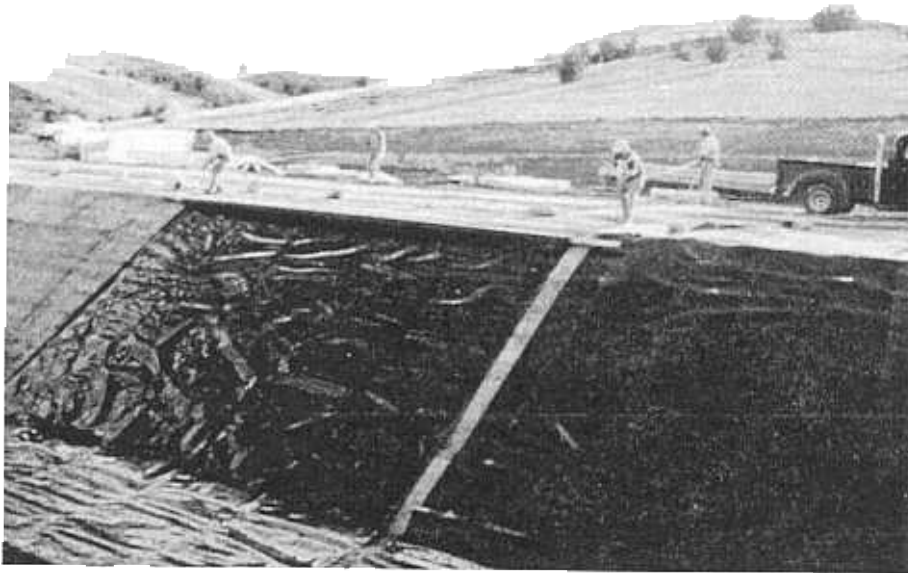


Figure 132. - Positioning HDPE geomembrane prior to heat welding the adjacent sheets.



Figure 133. - Heat-welding HDPE geomembrane in Mirdan Canal.



Figure 134. - Installation of fabric form concrete protective revetment material. Note anchor trench for HDPE and fabric materials. After installation of the fabric, as shown on figure 135, a concrete grout mix will be pumped into the fabric to form a hard-surface lining to protect the HDPE geomembrane.

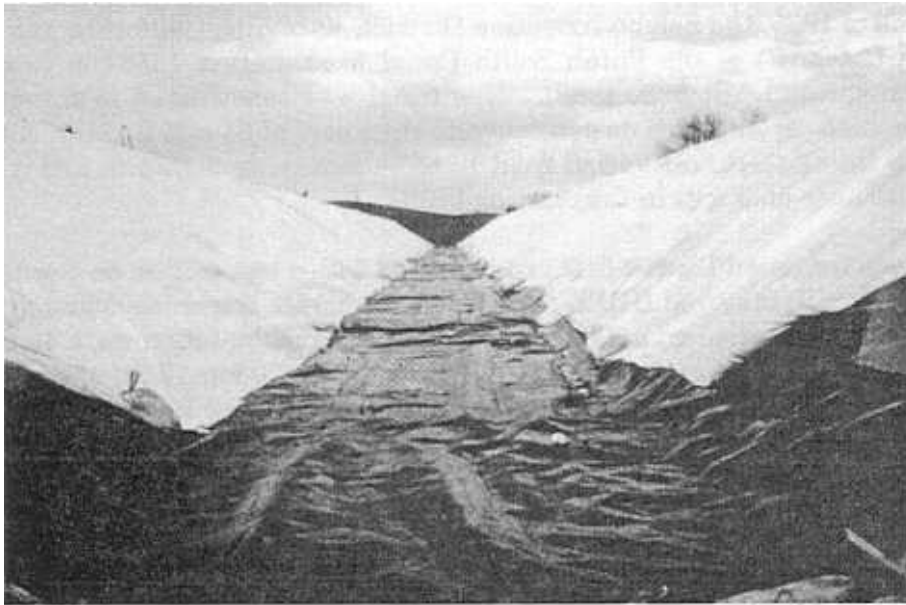


Figure 135. - View of fabric form concrete protective revetment material on side slopes prior to injection of concrete grout.



Figure 136. - View of completed repair section in Mirdan Canal.

2 Putah South Canal

In the fall of 1989, the Solano Irrigation District, Vacaville, California, rehabilitated about 1500 m (5,000 ft) of the Putah South Canal from station 1559+00 to station 1610+16 (Straubinger and Mitchell, 1989). This canal was constructed in the early 1950s as a concrete-lined canal with a design concrete thickness of 64 mm (2.5 in). Tests have shown that the lining thickness varied from 13 to 64 mm ($\frac{1}{2}$ to 2-1/2 in), and it has continually leaked because of cracks in the existing lining.

The Solano Irrigation District first experimented with a test section on Byrnes Lateral using 1.5-mm (60-mil) textured HDPE and various shotcrete thicknesses and differing amounts of fibermesh reinforcement in the mix. For the main rehabilitation work on the Putah South Canal, they used 1.0-mm (40-mil) textured HDPE with 50 mm (2 in) of shotcrete lining that had 1.2 kg/m³ (2 lb/yd³) of fibermesh reinforcement in the mix to reduce cracking. The geomembrane was nailed into the existing concrete along the top of the berm and the transverse seams were hot wedge welded. The shotcrete was then applied over the geomembrane. Open transverse joints at about 3.7-m (12-ft) centers were tooled into the shotcrete. The rehabilitation work is shown on figures 137 to 141.

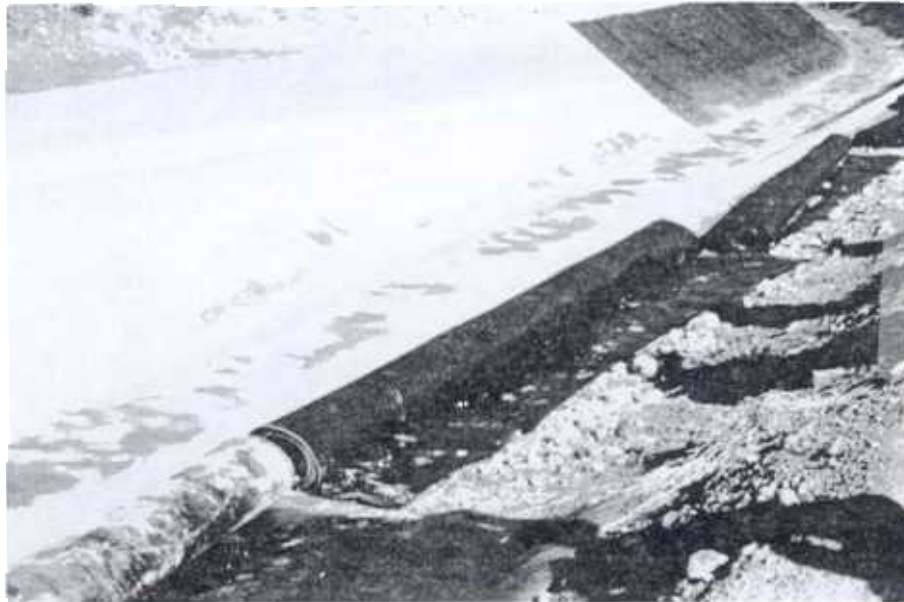


Figure 137. - Use of shotcrete/geomembrane system to repair concrete lining in Putah South Canal, Solano Irrigation District, California. View shows installation of 1.0-mm (40-mil) texturized HDPE lining.

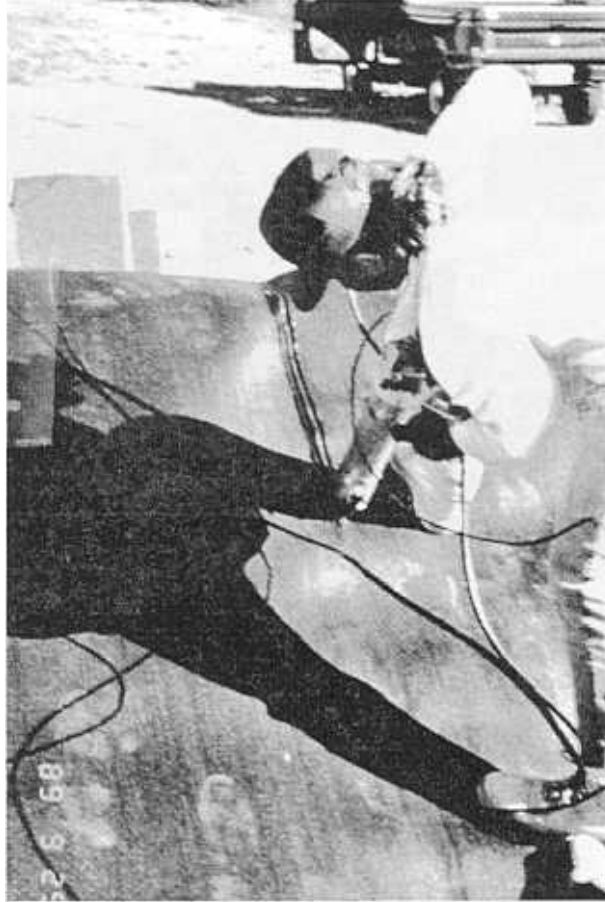


Figure 138. - Field seaming of texturized HDPE lining using hot welding methods.



Figure 139. - View of installed texturized HDPE geomembrane in Putah South Canal. About 1500 m (5,000 ft) of concrete lining were repaired.



Figure 140. - Applying shotcrete to texturized HDPE lining in Putah South Canal. Thickness of the shotcrete was about 51 mm (2 in).



Figure 141. - Completed repair section on Putah South Canal. Repair work was accomplished the fall of 1989.

In January 1992, after 26 months of service, Solano Irrigation District personnel reported (Straubinger, 1992) that they were pleased with the results of the rehabilitation work. The previous soil saturation/water leakage problems down slope from the canal are no longer a problem. Before the repair work, the water level in the canal was purposely kept low; after repairs, the water level could be raised to its design level. They also reported that the canal has been drained and cleaned at least twice since the repair work without incurring damage to the shotcrete lining. The performance of this repair will continue to be monitored.

3. Tucson Aqueduct Reach 3

About 2.4 kilometers (1.5 mi) of the Tucson Aqueduct Reach 3 concrete lining was found to be cracked, broken and buckled because of settlement of saturated foundation materials. To minimize repair time and cost, a geomembrane was selected rather than overexcavation and replacement of the subgrade and concrete canal lining.

Laboratory testing (Comer and Dewey, 1995) suggested that textured VLDPE would be the preferred lining material because of its excellent bi-axial elongation properties. In addition, VLDPE exhibits some elastomeric properties which enhance its resistance to puncture. This additional "toughness," which is reflected in higher tear strengths than PVC, was seen as an advantage during construction of this project. To reduce the effects of thermal expansion, which causes wrinkling of the geomembrane, a white-surfaced material was selected.

Repairs took place in November 1994. Figure 142 shows geomembrane placement following subgrade preparation. Specifications required removal of concrete chunks or smoothing of existing surfaces to provide no offsets greater than 20 mm (3/4 in). Following geomembrane placement, a 75-mm (3-in) layer of shotcrete was applied to the geomembrane surface as shown on figures 143 and 144. This repair will be monitored to determine its effectiveness.



Figure 42 Unrolling geomembrane for pipeline at the Tucson Aqueduct Reach repair



Figure Shotcreting the VLDPE textured geomembrane at the Aqueduct Reach

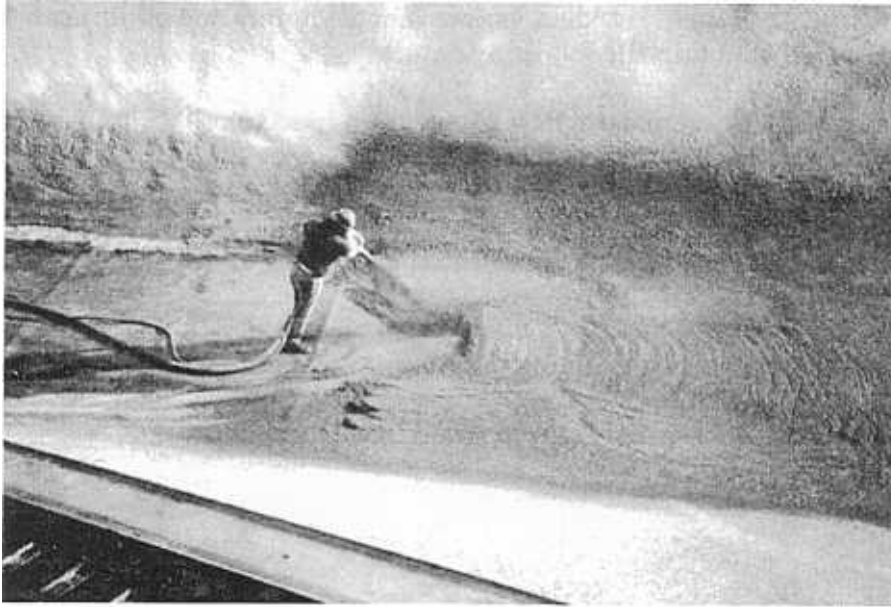


Figure 144. - Shotcreting over the geomembrane in the canal invert of the Tucson Aqueduct Reach 3.

Concrete Rehabilitation Conclusions

As part of the recently initiated studies, various manufacturers and other users of plastic linings are being contacted to obtain the following data:

1. Case histories on where plastic liners have been used to rehabilitate concrete linings and other hydraulic structures.
2. Recommendations on procedures for repairing the concrete before installation of the plastic lining.
3. Recommendations on materials and methods for joining or bonding the plastic lining to the concrete structure.

A report will be prepared summarizing the findings when the study is completed. Additional studies are needed to evaluate the various lining materials and develop installation techniques that local O&M forces can use.

Underwater Lining

For a number of years, Reclamation has been interested in developing seepage control methods for leaky, unlined irrigation canals that cannot be easily dewatered for lining because of water delivery commitments. The search for a practical and economical solution to this problem has led to several approaches. For example, an underwater installation of a prefabricated bituminous canal lining was attempted on the Yuma Project in 1956. Also, studies have been conducted on chemical soil sealants for reducing seepage. Results of these studies indicated that effectiveness of the seal depended upon the soil type, and long term durability was questionable. Also, some concern existed about the effect on aquatic life in the canals from the use of certain chemical agents.

Between 1989 and 1992, Reclamation conducted a research program to study methods and materials for the underwater placement of a plastic lining system using a concrete protective cover. Development of this technology will permit the lining of earthen canals without draining them and will also provide an alternative to building new, parallel canals.

As part of the research program, a 2.4-km (1.5-mi) demonstration section was constructed on the Coachella Canal near Niland, California (Morrison, 1990; Edwards, 1990; Rohe, 1991). The lining system consisted of 0.75-mm (30-mil) PVC with a 115-g/m² (3.4-oz/yd²) non-woven geotextile bonded to the top surface of the geomembrane covering the slopes. The purpose of the geotextile was to provide increased friction to prevent slippage of the 75-mm (3-in) concrete cover during placement on the 2.5:1 side slopes. A special mix containing an anti-washout additive was used to prevent erosion of the concrete during the underwater placement (Kepler, 1990). Photographs taken during the installation of the demonstration section (completed in the spring of 1991) are shown on figures 143 to 149. A separate report summarizing the laboratory and field tests associated with this study was published in 1994 (Bureau of Reclamation, 1994d).

The underwater lining technology is also applicable to placement in the dry. For example, the concrete/geomembrane system could be used to avoid overexcavation in expansive shales or clays, gypsiferous and loessial soils, and could also be placed in direct contact with high-sulfate soils.

Bottom-Only Lining

In special situations, soil conditions are such that seepage occurs primarily in the vertical direction. Under such conditions, a bottom-only lining may be attractive. Because a completely watertight canal is generally not necessary, the small amount of seepage from the side slopes can be tolerated if the cost advantage is sufficient. Another advantage of this type of lining system is that the problem of soil cover stability on side slopes is eliminated. Soil conditions which exhibit this seepage pattern are found in the loessial soils in some areas of Kansas and Nebraska. A field study, in which 0.25-mm (10-mil) PVC was placed only on the canal invert (as shown on figure 150), was performed by Reclamation's Nebraska-Kansas Projects Office, Grand Island, Nebraska, and showed a 50- to 55-percent seepage reduction.

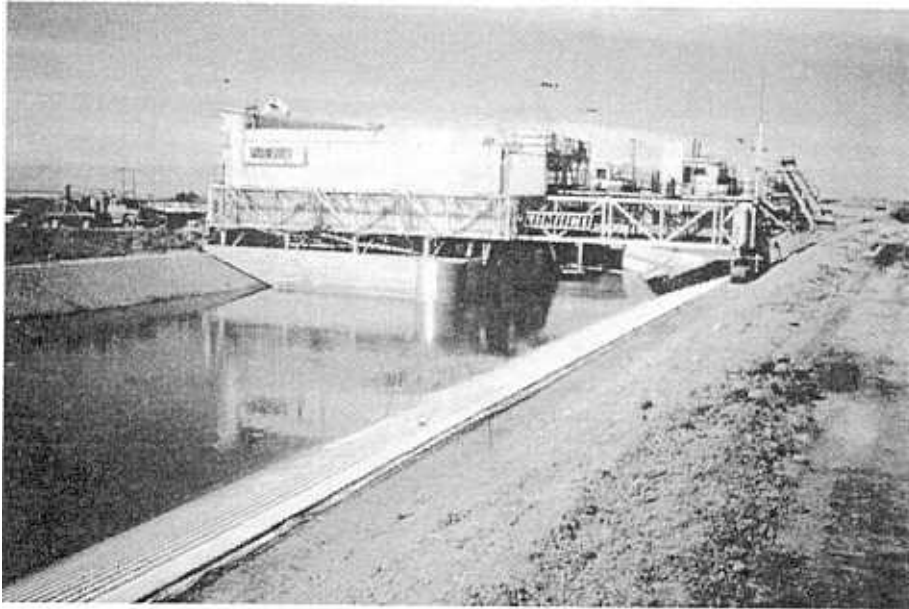


Figure 145. - Lining machine for installing geomembrane and concrete protective cover in one operation. The upper deck is used to store the PVC geomembrane and provides a working space for making the transverse field seams.

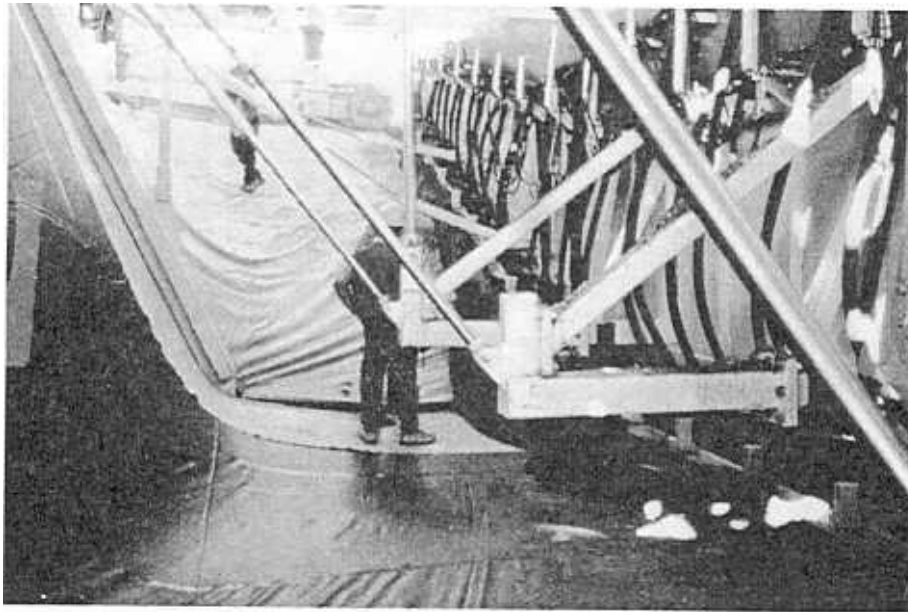


Figure 146. - View under lining machine showing geotextile and PVC on the 2.5:1 side slopes. Slip form paver is located at right side.

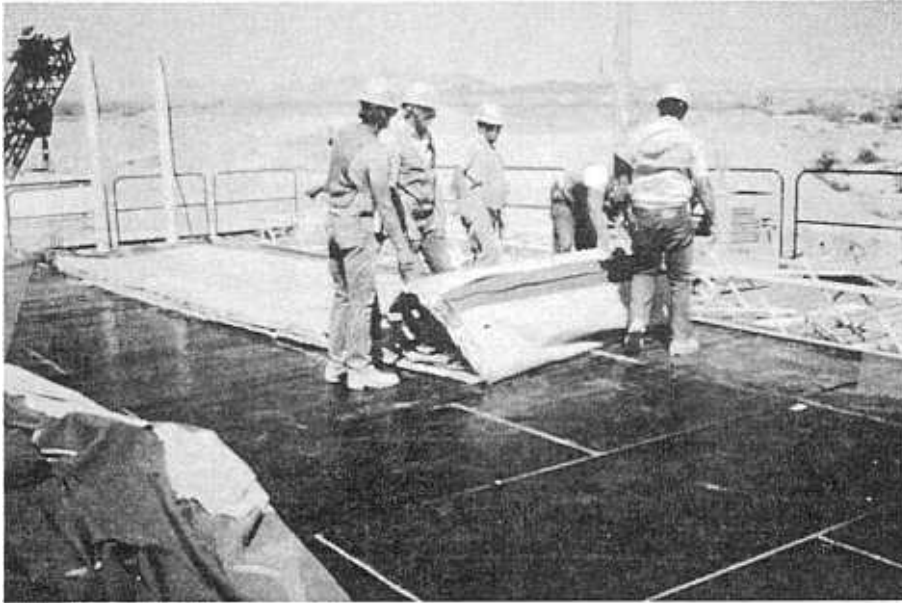


Figure 147. - Unfolding PVC/geotextile composite lining on paver deck prior to making transverse field seam.

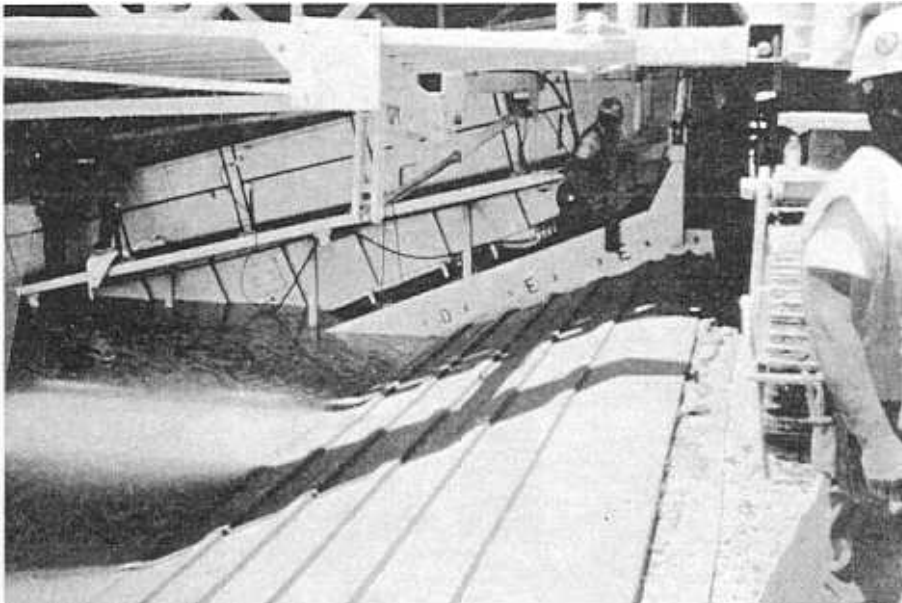


Figure 148. - Underwater lining of the Coachella Canal. PVC lining can be seen at top of slope. The animal escape curbs, formed in the lining, are also visible.



Figure 149. - Completed demonstration section on the Coachella Canal near Niland, California. The installation was completed in the spring of 1991.

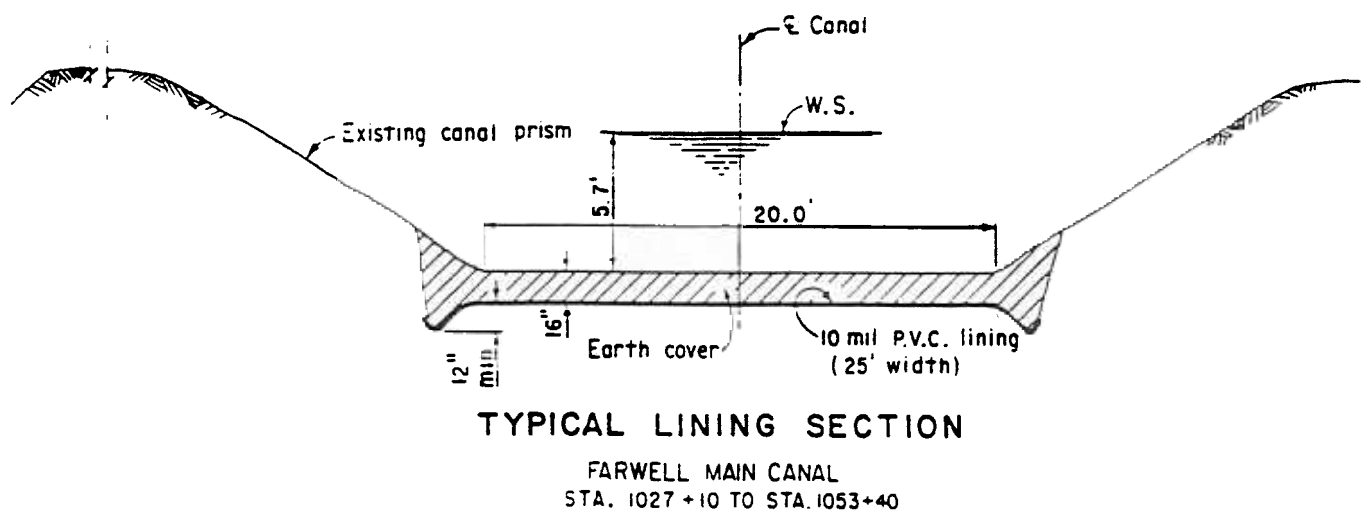


Figure 150. - Bottom only lining section on Farwell Canal, Middle Loup Division, Farwell Unit, Nebraska.

The following canals were studied:

1. Farwell Main Canal, Middle Loup Division, Nebraska
2. Franklin Canal, Nebraska-Bostwick Unit, Nebraska
3. Upper Meeker Canal, Frenchman-Cambridge Division, Nebraska

Results of the field study (Bureau of Reclamation, 1986a) are shown in table 36.

Table 36. - Results of bottom-only lining study conducted by Nebraska-Kansas Projects Office, Grand Island, Nebraska.

Location	Canal size*		Seepage loss ft ³ /ft ² /day		% reduction
	Q	B	Before lining	After lining	
Farwell Main Canal, Station 1027+10 to Station 1053+40	290	18	0.56	0.27	52
Franklin Canal, Station 168+00 to Station 184+76	230	14	1.01	0.45	55
Upper Meeker Canal, Station 311+68 to Station 341+00	284	16	1.13	0.56	50

*Q denotes flow in ft³/s.

B denotes bottom width in feet.

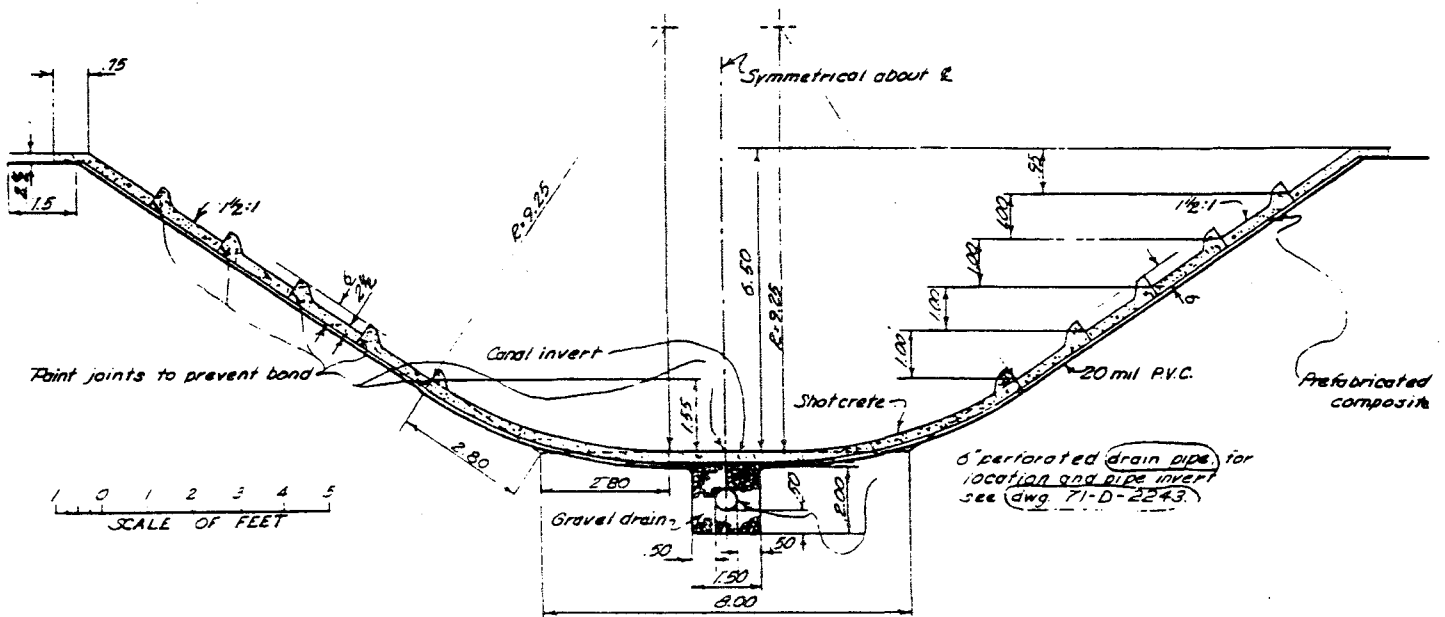
As part of the study conducted on the Middle Loup Division, a full prism lining of 0.5-mm (20-mil) PVC was installed in the Farewell Lower Main Canal (Bureau of Reclamation, 1982). Based on discussions with field personnel, the performance of the linings has been satisfactory (Frobel and Gray, 1984). The linings have not caused any maintenance problems. Both installations involved covering the PVC membrane with loessial material. One small slippage (0.3 m² [3 ft²]) of the cover material has occurred on the side slope of the full prism lining near a farm turnout structure. The area was repaired once and has since performed satisfactorily. Crop losses caused by canal seepage prior to the geomembrane installation have been eliminated. From the District's perspective, this project has been very successful.

Barriers for Drainage Systems

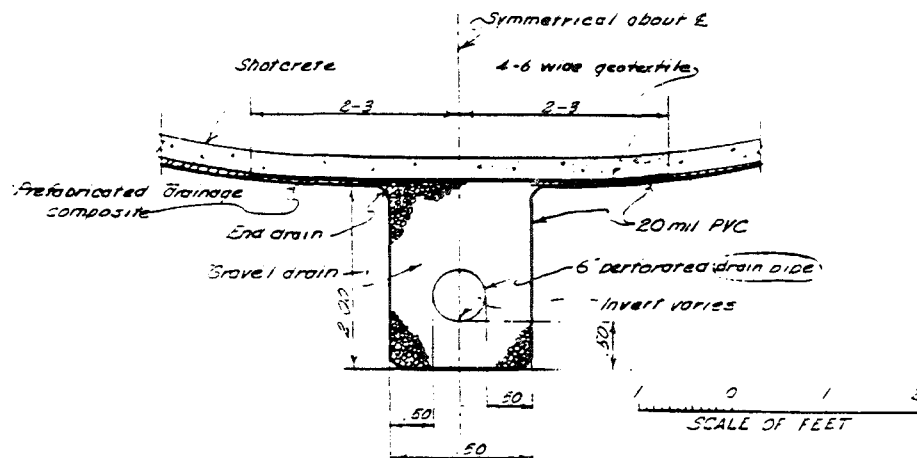
To allow winter operation in the Towaoc Canal, Dolores Project, Colorado, a special drainage system shown on figure 151 was installed in the reach of the canal lined with concrete. This reach, located on a hillside, is about 1.6 km (1 mi) in length. This PVC lining system was selected because of the short construction season, steep canal slopes (1.5:1), and hillside location, requiring an extremely watertight system to prevent any embankment failures. The specifications (Bureau of Reclamation, 1990b) called for shotcrete, but the Contractor elected to use concrete because of a lack of experienced shotcrete applicators in the area.

The drainage system, installed under the concrete lining, consists of a 0.5-mm (20-mil) thick PVC geomembrane covered with a synthetic drainage composite. The drainage system collects seepage through the concrete lining to prevent hydrostatic back pressure during canal drawdown. The system will be operated intermittently in the winter to provide stock water for some users.

Towaoc Canal was built as a salinity feature to replace existing Montezuma Valley Irrigation Company ditches, and supplies water to Ute Mountain Indian tribal lands west of Cortez. Towaoc Canal replaces lower Hermania Lateral, Highline Ditch, and Rocky Ford Ditch. Canal construction, shown on figures 152 to 156, was completed in the summer of 1990.



DETAIL OF LINING



DETAIL OF DRAIN

Figure 151. - Cross sectional view of Towaoc Canal, Reach 1, Dolores Project, Colorado. A special drainage system was installed in the concrete-lined reach located on a hillside.



Figure 152. - Underdrain trench being excavated in Towaoc Canal, Reach 1, Dolores Project, Colorado. Photograph taken August 1990.



Figure 153. - View showing placement of concrete lining over synthetic drainage composite material in Towaoc Canal.



Figure 154. - Another view of concrete placement in Towaoc Canal. Animal escape curbs are being formed into lining.

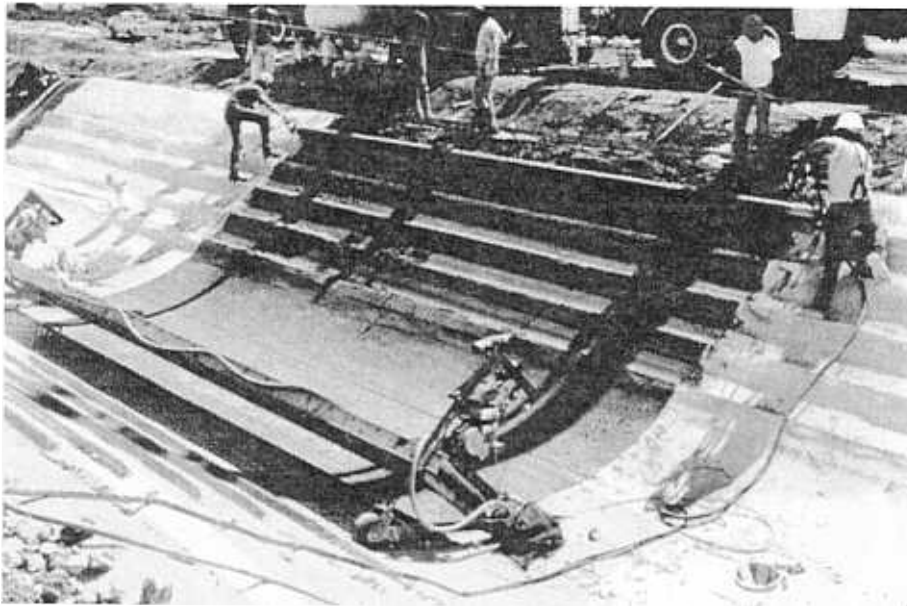


Figure 155. - Completing placement of concrete panel on Towaoc Canal.



Figure 156. - Aerial view showing placement of concrete lining in Towaoc Canal.

LABORATORY STUDIES

Chemical Analyses

To determine the extractable (plasticizer) content of the retained (original) and in service PVC geomembrane samples, the following procedure was used:

1. A preweighed sample of about 5 grams was extracted with 200 cm³ of ethyl ether (soxhlet extraction refluxing for 18 to 20 hours).
2. The ether containing the extract was then placed in a teared beaker, and the ether was allowed to evaporate to concentrate the extractables. (Note: all of the ethyl ether was driven off during this step). By reweighing the beaker, the percent extractables were determined.

Test results concerning the plasticizer content are summarized in tables 7, 9, 11, 12, 14, and 15.

Effects of Folds on the Performance of PVC Geomembranes

As previously mentioned, some folding and wrinkling of the PVC geomembrane may occur during canal construction, especially for installation around curves. A limited laboratory study was conducted to study the effects of folds. Both folded and unfolded tear and tensile test specimens of 0.5-mm (20-mil) PVC were subjected to the following aging conditions:

1. Standard environment, 23 °C (73 °F), 50 percent relative humidity
2. Water immersion, flowing tap water at 13 °C (55 °F)
3. Oven aging at 38 °C (100 °F)

The specimens were tested after 4, 13, 26, and 52 weeks of aging. Test results summarized in table 37 indicate that the folds caused no adverse effects. Before testing, the folded specimens were examined under 5X magnification, and no signs of cracking were observed.

Table 37. - Effect of folds on the tear and tensile properties of PVC geomembranes.

Test Conditions*	Test Period (weeks)	Tensile strength, lbf/in		Elongation, percent		Graves tear, lbf	
		F	U	F	U	F	U
Room	0	-	53.8	-	305	-	5.4
	4	54.1	52.3	309	308	5.3	5.4
	13	51.8	53.1	316	329	5.2	5.4
	26	54.5	54.5	305	304	5.3	5.6
	52	53.8	53.2	309	306	5.6	5.4
Water	0	-	53.8	-	305	-	5.4
	4	54.9	55.9	318	320	5.7	5.6
	13	50.2	51.5	311	317	5.0	5.3
	26	55.1	55.1	313	310	5.5	5.3
	52	51.1	52.5	291	314	5.3	5.4
100 °F	0	-	53.8	-	305	-	5.4
	4	53.2	55.1	310	317	5.4	5.5
	13	50.2	51.2	311	315	5.3	5.4
	26	54.0	50.8	302	288	5.9	5.4
	52	50.9	51.0	281	284	5.3	5.3

*Room conditions: 50 percent relative humidity; 73 °F.
water: flowing Denver tapwater between 50 and 60 °F.

F denotes folded
U denotes unfolded

Seaming of LDPE Geomembrane

With the initial results indicating that a bottom-only lining may be an effective, low-cost method of seepage control in loessial soils, several other irrigation districts in the GP (Great Plains) Region have indicated an interest in the concept, and LDPE has been mentioned as a possible lining candidate. Results of field studies conducted on LDPE (also referred to as "visqueen") lining indicate they have excellent aging characteristics, but are difficult to field seam because of their inertness (Suhorukov et al., 1982).

A limited laboratory study was conducted to evaluate the effectiveness of a self-adhering waterproof membrane material to field seam LDPE linings. This membrane material, developed primarily for waterproofing concrete surfaces below grade, consists of an LDPE plastic film 0.1 mm (4 mil) thick coated on one side with rubberized asphalt 1.4 mm (56 mil) thick. The membrane material is supplied in rolls 0.9 m (3 ft) wide, interwound with a special release paper which protects the adhesive surface until ready for use. To field seam the LDPE plastic, adjacent sheets were simply overlapped, and then a strip of the self-adhering waterproof membrane 75 to 100 mm (3 to 4 in) wide was placed and then hand rolled to join the two plastic sheets together. The LDPE plastic used in this study came from a sample of a lining installed in a bottom-only application on the Mirage Flats Irrigation District, Hay Springs, Nebraska, in the fall of 1983.

Samples of field seams were prepared, placed in a dip tank, and then tested after 4, 13, 26, and 52 weeks of immersion in Denver running tap water with the temperature near 13 °C (55 °F). Both shear (ASTM: D 882) and peel (ASTM: D 413) tests were conducted on the field seams. Also, the tensile strength of the 0.25-mm (10-mil) LDPE plastic was determined before and after 52 weeks of water immersion.

Test results are summarized in table 38. These results indicated that both shear and peel strength values of the field seam experienced a slight decrease after 1 year of water immersion. For example, the seam strength in shear decreases from 2.7 N/mm (15.5 lbf/in) width to 2.6 N/mm (14.8 lbf/in) width, and the peel strength from 1.0 N/mm (5.8 lbf/in) width to 0.7 N/mm (4.2 lbf/in) width. The retained seam strength should be sufficient to provide satisfactory service because the in situ field seams will be subjected to very little peel and shear stresses. This lack of stress can be attributed to the fact that the seam will lie in a horizontal plane and will be protected with an earth cover 0.3 to 0.45 m (12 to 18 in) deep.

Very little change occurred to the tensile strength of the LDPE lining after 1 year of water immersion. The original value was 4.4 N/mm (24.9 lbf/in) width, compared to 4.3 N/mm (24.5 lbf/in) width after 1 year of immersion.

Table 38. - Results of laboratory tests on LDPE field seams for use in bottom-only lining applications.

Property	Original Values	Water Immersion (weeks)			
		4	13	26	52
Seam shear strength, N/mm (lbf/in)	2.7 (15.5)	2.6 (14.9)	2.7 (15.4)	2.5 (14.4)	2.6 (14.8)
Seam peel strength, N/mm (lbf/in)	1.0 (5.8)	1.1 (6.3)	1.1 (6.4)	0.8 (4.3)	0.7 (4.2)
Breaking strength of LDPE lining, N/mm (lbf/in)	4.4 (24.9)	—	—	—	4.3 (24.5)

Volatility Tests

Volatility tests, ASTM designation: D 1203, Method A, "Test Method for Volatile Loss From Plastics Using Activated Carbon Methods," were conducted on several samples of PVC, VLDPE, and EIA geomembranes. Test specimens from each sample were removed and the weight loss determined after 1, 3, 7, 14, 28, and 56 days of aging.

Test results, summarized in table 39, indicated that the weight loss for PVC depended on source (manufacture) and thickness. The PVC material exhibiting the lowest weight loss came from a sample of a lining used to repair Palmer Lake Dam No. 2 (Hammer, 1991), an old concrete surface structure near Denver, Colorado. The PVC materials (manufacturer A) showing the greatest weight losses are no longer being produced. Test results also indicated that the PVC geomembranes exhibited higher weight loss than that noted for the VLDPE and EIA materials.

Table 39. - Results of 56-day volatility tests on geomembranes.

Material	Lab No. (mfg)	Weight Loss (%)					
		Days of Aging					
		1	3	7	14	28	56
20-mil PVC	B-7125 (A)	1.67	3.99	5.76	9.04	17.10	22.30
20-mil PVC	23271 (B)	0.87	1.38	2.15	3.42	5.44	8.47
20-mil PVC	21964 (C)	0.85	1.52	2.67	4.14	6.45	9.97
30-mil PVC	B-7126 (A)	0.40	1.91	4.39	6.26	9.48	15.80
30-mil PVC	22838 (B)	0.40	0.68	1.17	1.94	3.45	5.44
40-mil PVC	23197 (C)	0.39	0.79	1.38	2.16	3.53	5.58
45-mil PVC	B-7127 (A)	0.46	0.95	1.73	4.84	7.72	12.20
40-mil PVC	23202 (D)	0.17	0.32	0.52	0.77	1.17	1.79
40-mil VLDPE	23272 (E)	0.10	0.14	0.21	0.26	0.34	0.39
20-mil EIA	22938 (F)	0.26	0.47	0.59	0.74	0.85	1.04
30-mil EIA	22939 (F)	0.33	0.50	0.76	0.99	1.28	1.55

Note: Test was conducted in accordance with ASTM D 1203, method A, "Test Methods for Volatile Loss from Plastics Using Activated Carbon Methods."

Outdoor Exposure

Samples of VLDPE, LDPE, EIA, and PP geomembranes were placed outdoors at the Denver Federal Center to determine their aging characteristics relative to possible use as exposed linings. For the outdoor exposure tests, specimens measuring 0.3 by 0.3 m (12 by 12 in), were placed on a 1 to 1 slope with a southern exposure for testing. Specimens have been tested after 2.5 years of exposure.

Test results to date for the VLDPE geomembranes are summarized in table 40, the LDPE in table 41, the EIA in table 42, and the PP in table 43. These results indicate that after 2.5 years of outdoor exposure, the 0.5-mm (20-mil) VLDPE cracked and experienced considerable stiffening. The 0.75-mm (30-mil) VLDPE sample shown on figure 157 cracked and failed at 5 years. The EIA, PP, and LDPE materials have exhibited very little change in tensile and tear strength properties after 2.5 years of outdoor exposure.

Table 40. - Results of outdoor exposure tests for VLDPE geomembranes.

Physical Properties	ASTM Test Method	Laboratory Sample No. 22936 Months of Aging			Laboratory Sample No. 22814 Months of Aging		
		0	12	30	0	12	30 <u>1</u>
Thickness, mm (mil)	D 751	0.59 (23.2)	0.64 (25.1)	SF	0.89 (35.0)	0.92 (36.3)	0.92 (36.4)
Tensile Strength, N/mm (lbf/in)	D 638, type IV specimens 2-inch gauge length	16.9 (96.6) L 15.7 (89.6) T	10.6 (60.7) L 12.4 (70.8) T	SF L T	22.8 (130) L 24.8 (142) T	21.9 (125) L 23.4 (134) T	23.8 (136) L 22.4 (128) T
Elongation, %	"	950 L 1026 T	720 L 850 T	SF L T	820 L 1055* T	850 L 1000* T	1665 L 1390 T
Tear Resistance N/mm (lbf/in)	D 1004	61.4 (13.8) L 58.3 (13.1) T	52.5 (11.8) L 45.4 (10.2) T	SF L T	67.6 (15.2) L 65.8 (14.8) T	78.7 (17.7) L 83.2 (18.7) T	78.7 (17.7) L 76.1 (17.1) T
Bonded Seam Strength in Shear, N/mm (lbf/in)	D 4437	7.5 (42.8)	7.2 (41.4) L	----	9.9 (56.6)	10.1 (57.9)	ND
Bonded Seam Strength in Peel, N/mm (lbf/in)	D 4437	5.3 (30.5) FTB	5.8 (33.0) FTB	----	7.3 (41.7)	7.9 (45.4) FTB	ND
Dimensional stability, 15 min at 100 °C (212 °F), % change	D 1204	-0.6 L -0.5 T	ND	----	-3.2 L -0.7 T	ND	ND

* No break, top limit of machine

** No break for 60 percent of specimens tested, top limit of machine

FTB denotes film tearing bond

ND denotes not determined

SF denotes sample failed

1/ in tensile test, a 1-inch gauge length was used.

Table 41. - Results of outdoor exposure tests for LDPE geomembranes.

Physical Properties	ASTM Test Method	Laboratory Sample No. 23299 Months of Aging				
		0	3	6	21	30
Thickness, mm (mil)	D 751	0.77 (30.4)	0.32 (30.0)	0.75 (29.8)	0.77 (30.2)	0.78 (30.7)
Tensile Strength, N/mm (lbf/in)	D 638, type IV specimens 2-inch gauge length	26.3 (150.4) L	25.7 (147.1) L	25.4 (145.3) L	26.5 (151.5) L	26.2 (149.9) L
		27.0 (154.3) T	26.4 (150.7) T	26.5 (151.7) T	26.8 (153.1) T	22.9 (131.0) T
Elongation, %	“ ”	1444 L	1411 L	1408 L	1444 L	1385 L
		1449 T	1426 T	1443 T	1449 T	1210 T
Tear Resistance N/mm (lbf/in)	D 1004	76.5 (17.2) L	73.9 (16.6) L	80.5 (18.1) L	90.3 (20.3) L	90.3 (20.3) L
		77.0 (17.3) T	88.6 (19.9) T	79.2 (17.8) T	89.9 (20.2) T	89.9 (20.2) T

Table 42. - Results of outdoor exposure tests for EIA (ethylene interpolymers alloy) geomembranes.

Physical Properties	ASTM Test Method	Laboratory Sample No. 22938 Months of Aging			Laboratory Sample No. 22939 Months of Aging		
		0	12	30	0	12	30
Thickness, mm (mil)	D 1593 Par. 9.1.3	0.53 (20.7)	0.56 (22.0)	0.54 (21.1)	0.78 (30.6)	0.78 (30.9)	0.79 (31.7)
Tensile Strength, N/mm (lbf/in)	D 882 2-inch gauge length	10.1 (57.9) L 9.6 (54.9) T	9.0 (51.7) L 8.9 (50.8) T	9.0 (51.2) L 9.0 (51.2) T	10.8 (61.9) L 10.2 (58.5) T	11.0 (62.6) L 10.8 (61.6) T	10.5 (60.1) L 10.8 (61.5) T
Elongation, %	"	406 L 443 T	337 L 379 T	406 L 362 T	307 L 331 T	313 L 338 T	341 L 294 T
Modulus at 100% Elongation N/mm (lbf/in)	"	6.1 (34.8) L 5.6 (32.2) T	6.6 (37.5) L 6.0 (34.5) T	6.3 (36.1) L 6.3 (36.1) T	8.3 (47.6) L 7.9 (45.1) T	8.5 (48.6) L 8.4 (48.2) T	8.7 (49.7) L 8.7 (49.8) T
Tear Resistance N/mm (lbf/in)	D 1004	29.4 (6.6) L 31.1 (7.0) T	33.8 (7.6) L 38.7 (8.7) T	(8.0) L (8.7) T	45.8 (10.3) L 43.1 (9.7) T	46.3 (10.4) L 47.6 (10.7) T	49.4 (11.1) L 54.3 (12.2) T
Dimensional stability % change 15 min at 100 °C (212 °F) 60 min at 100 °C (212 °F)	D 1204	-4.6 L, 1.4 T -5.1 L, 1.1 T	ND	ND	-2.7 L, 2.9 T -2.9 L, 0.4 T	ND	ND

L denotes longitudinal direction.

T denotes transverse direction.

ND denotes not determined.

Table 43. - Results of outdoor exposure tests for PP geomembranes.

Physical properties	ASTM test method	Laboratory sample No. 23297 Months of Aging				
		0	3	6	21	30
Thickness, mm (mil)	D 751	0.78 (30.8)	0.82 (32.5)	0.82 (32.5)	0.83 (32.6)	0.81 (32.1)
Tensile strength, N/mm (lbf/in)	D 638, type IV specimens 2-inch gauge length	16.6 (95.1) L	18.6 (106.3) L	18.0 (103.0) L	17.1 (97.7) L	17.7 (101.2) L
		14.4 (82.5) T	17.3 (99.1) T	17.8 (101.6) T	17.8 (101.6) T	17.7 (101.4) T
Elongation, %	"	1157 L	1185 L	1142 L	1080 L	1114 L
		1146 T	1282 T	1281 T	1274 T	1233 T
Tear resistance, N (lbf/in)	D 1004	64.1 (14.4) L	50.3 (11.3) L	50.7 (11.4) L	71.6 (16.1) L	82.7 (17.7) L
		57.4 (12.9) T	51.2 (11.5) T	51.6 (11.6) T	70.8 (15.9) T	81.4 (18.7) T

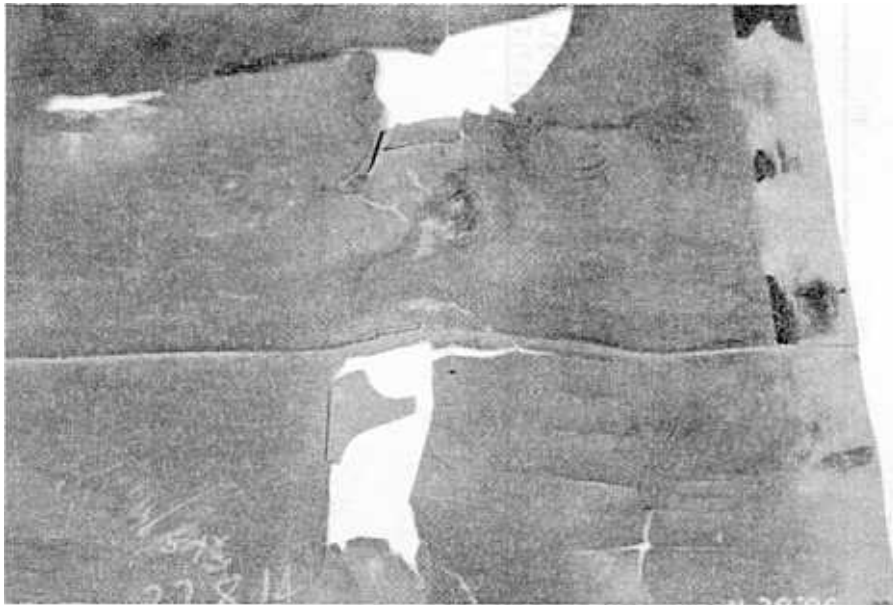


Figure 157. - Condition of 0.75-mm (30-mil) VLDPE sample after 5 years of outdoor exposure. Sample was in a very brittle condition.

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Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.